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Fire Hazard Assessment of Shipboard Plastic Waste Disposal Systems

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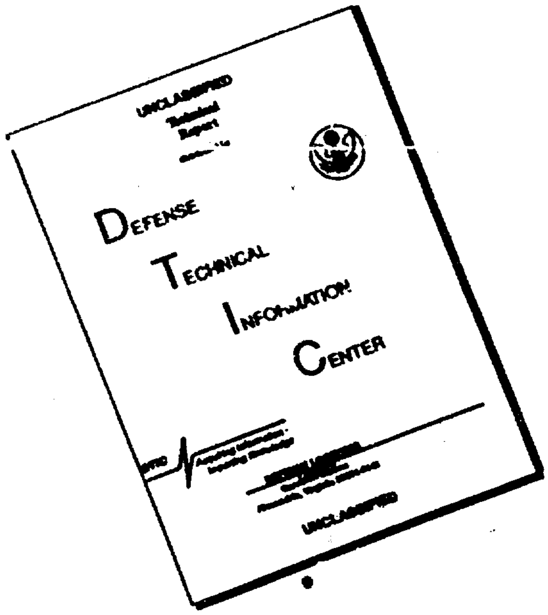

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A fire hazard assessment of proposed shipboard plastic waste processing systems was conducted. The evaluation included small-scale ignition and heat release rate studies of prototype processed plastic as well as mathematical modeling of expected fire conditions in compartments housing the processor unit and in storage of processed plastic. An evaluation of the impact of detection and automatic sprinkler protection was also conducted. The study concluded that storage of processed plastic was preferred over storage of unprocessed materials, that there was little risk of ignition of plastics caused by the processor, and that any residual risk associated with storage of processed plastic could be eliminated by the provision of an automatic sprinkler system in the compartment housing the processing unit. Limitations on storage height of processed materials are also specified.

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Fire Hazard Assessment of
Shipboard Plastic Waste Processing Systems

1.0 INTRODUCTION

National and international environmental concerns and current regulations spanning state, local, federal, and international governing bodies have made it increasingly difficult to continue with overboard disposal of wastes produced by Naval ships. To address these issues, the Navy has implemented the Shipboard Waste Management Program. This program is concerned with the development of shipboard processes, equipment, and other methods to manage waste production, processing, and disposal. As part of this program, a plastic waste disposal (PWD) unit has been developed in order to meet regulations which ban overboard disposal of plastic waste after January 1, 1994 [1].

The processor takes bulk waste, shreds it, compacts it, and heats it while passing steam through the chamber and ejects a stable, compact, high density block of plastic waste.

This process achieves the following with regards to problems associated with plastic trash storage:

- The volume of plastic waste undergoes a significant reduction, 30 to 1, which means that for a ship with a complement of 300 persons, a month of processed plastic waste can be stored in the area that would contain a single day's accumulation of bulk, unprocessed trash;

- The plastic waste is heated in the compression chamber at temperatures over 149°C (300°F) for time periods long enough to ensure that food residue which can contaminate waste plastic is thoroughly baked, significantly reducing the sanitation and odor problems that plague bulk storage methods; and

- Produces a stable block which will hold up under long term storage conditions and may be recyclable.

This report summarizes the results of a project which evaluated the fire hazard of compressed plastic waste produced by plastic waste processor units. The report also includes a specific hazard analysis of the impact of ignition of processed plastic waste and the potential of installed protection methods in controlling the resultant fire impact.

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2.0 SYSTEM DESCRIPTION

Diagrams of the plastic waste processor unit are presented in Figs. 1 and 2. The processor is simple in design and consists of five subsystems [2].

The first is the Feed and Size Reduction Subsystem. This system takes the bulk plastic waste which is manually loaded into the infeed hopper and shreds the plastic before it enters the compression and heat chamber. It is shredded by passing through two counter-rotating carbide/tool steel "screw" blades. These blades are sharp enough, and there is sufficient torque to process inadvertent pieces of metal and glass that may be intermingled with the waste plastic. In fact, both aerosol cans and butane lighters have been processed without incident.

The shredded plastic enters the Load Application Subsystem after passing through the shredding blades. This system forces the commingled shredded waste into the compression/melt chamber. Once there is sufficient shredded waste, the compression ram, which is operated by a push-pull chain and a gear box/motor assembly, pushes the waste into the portion of the compression chamber where the heating and cooling takes place.

The third subsystem is the Ram Chamber Heat/Cool Subsystem. Here, the shredded waste is continually loaded under compression from the Ram while resistance heaters heat the compression area to an average temperature of approximately 163°C (325°F) with edge and face temperatures approaching 177°C (350°F). This substantially softens the plastic enhancing the volume reduction and "cooking" any residual food to minimize the sanitation and odor issues. The cooling system uses a heat exchanger and seawater to cool the chamber and the plastic block which facilitate handling of the compressed plastic waste block.

The Block Ejection System removes the block from the compression/heat chamber. Once the block has cooled sufficiently, the ejection door shears the waste block off the face of the compression ram.

The final subsystem is the Control Subsystem. This system is comprised of a programmable logic controller which monitors various sensors to automate the process as much as possible. This system includes temperature, pressure, torque, and position monitoring in order to control the processes.

A complete cycle of the system takes approximately 100 minutes and produces a single block of processed plastic waste measuring approximately 58 x 48 x 5 cm (23 x 19 x 2 in.) and weighing approximately 44 kg (20 lb). The cabinet which houses the processing equipment is equipped with two high flow rate fans which provide an air change every five minutes inside the processor.

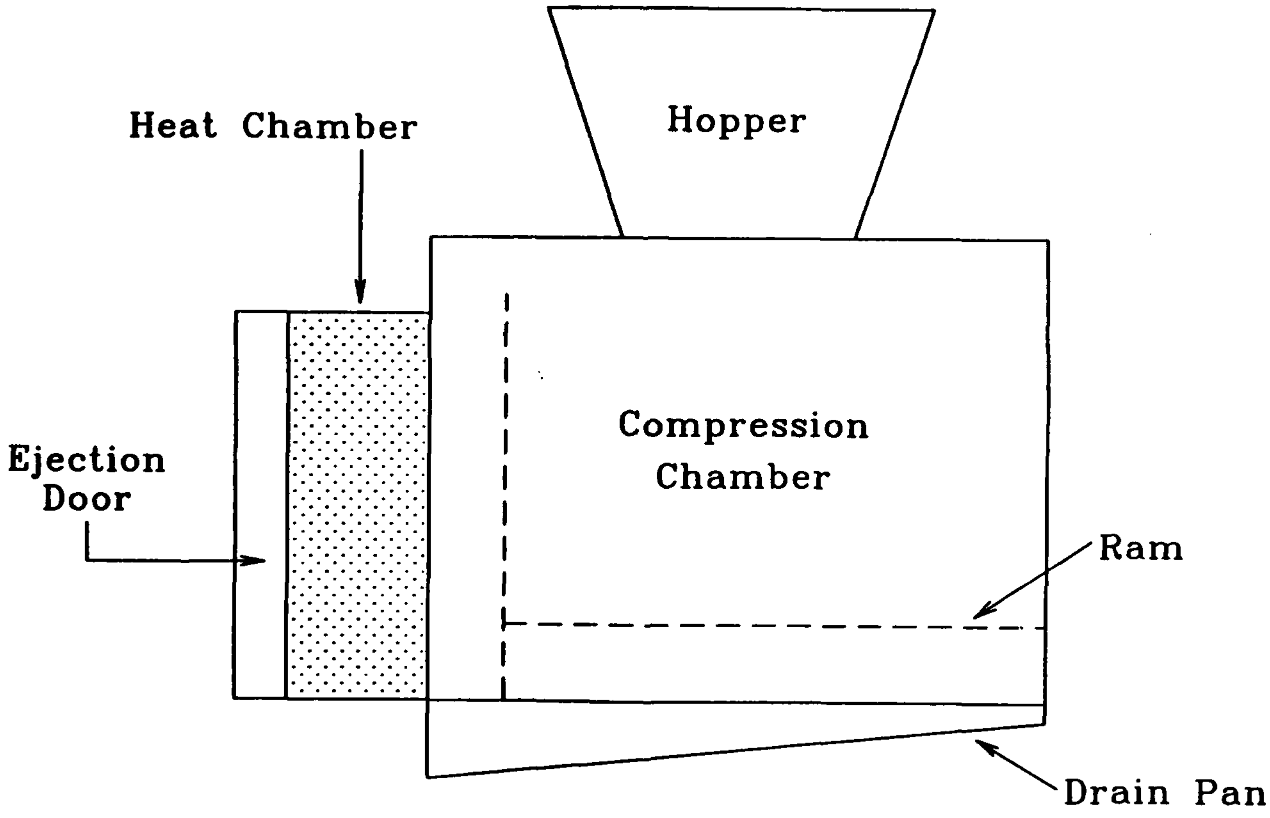

Fig. 1 - DTRC inhouse model plastic waste processor (300 man crew maximum)

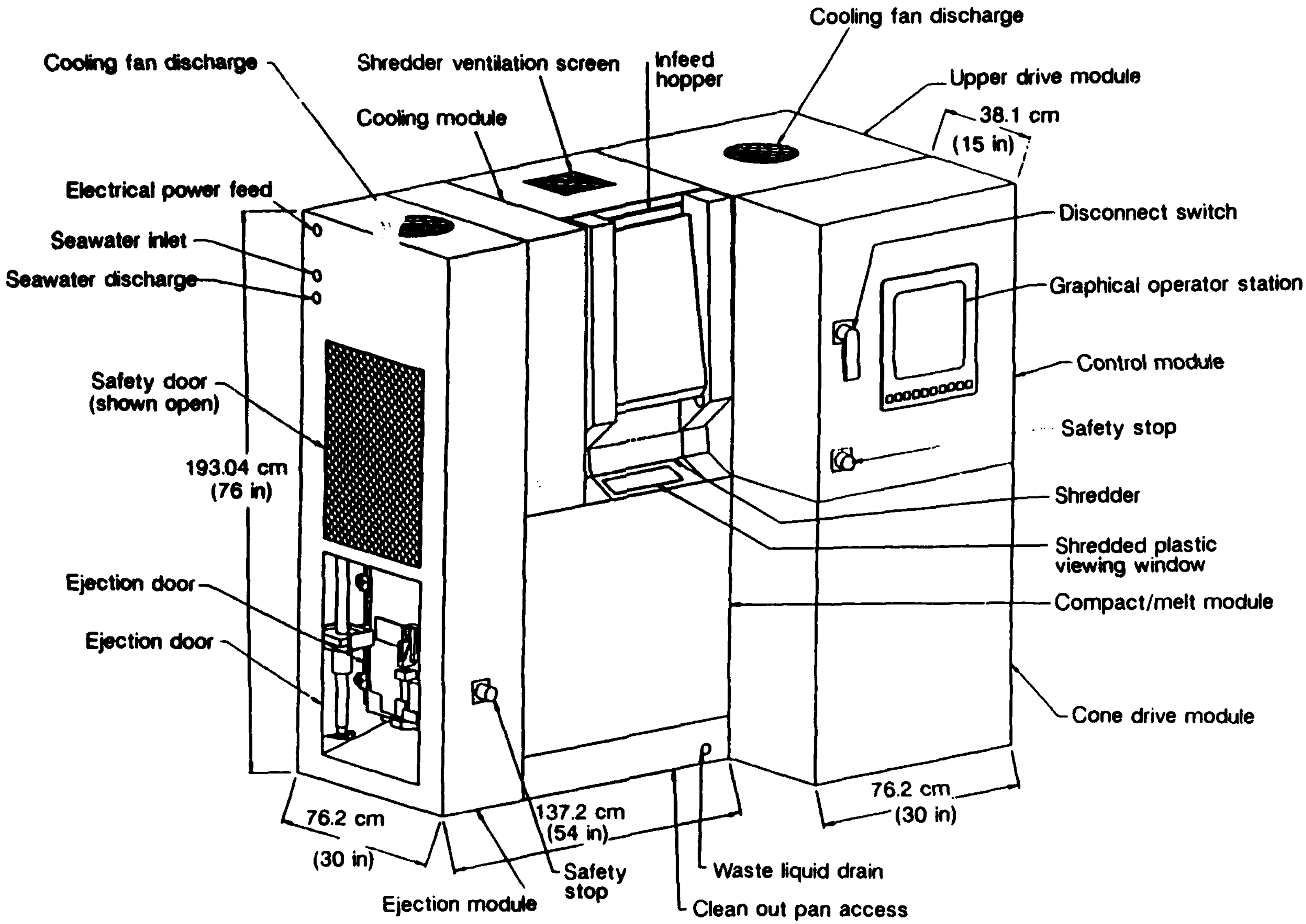

Fig. 2 - Commercial plastic waste processor evaluated for shipboard use

3.0 ANALYSIS

A fire hazard analysis of the Plastic Waste Disposal system has been conducted which includes the following areas:

- fuel load analysis;
- bulk plastic versus compressed/processed plastic storage;
- ignitability testing;
- small scale heat release rate testing; and
- mathematical modeling of the consequences of a fire involving storage of processed plastic materials.

The storage of plastic items raises important fire protection issues regardless of storage configuration or commodity form. Regardless of the form, the tests and research conducted as part of this project confirm that the potential heat release rate per unit area of burning surface is high, comparable to that of common thermoplastics such as PMMA and polyurethane. However, the storage of compacted plastic waste normally exposes less surface area to burning; hence, the processed plastic waste block form is inherently less of a hazard than bulk form as the following analysis shows. The conversion of plastic waste to block form eliminates part but not all the hazard. This report is directed toward evaluating the need to protect the ship and crew from the remaining fire hazards involved with the mass of plastic materials that could be stored in a single location.

The volume reduction achieved by the PWD units, 30:1, is very significant from the practical point of view. This is reflected in Table 1 which illustrates the impact of the volume reduction where, after a week, the processed blocks would fit in one-third of a Navy 1.2 m (4 ft) triwall corrugated cardboard container while the bulk trash would occupy 9.5 Navy 4 ft triwalls. Figure 3 illustrates the standard Navy triwall.

A one-month's accumulation of the processed blocks stored in one and one-third triwalls would occupy less than one-tenth of a 2.4 x 3.7 m (8 x 12 ft) room while the bulk plastic would require 2.3 compartments measuring 2.4 x 3.7 m (8 x 12 ft) and over 40 triwalls. Clearly, if plastic waste is going to be stored on board the ship, some type of volume reduction method must be implemented strictly from an effective space usage perspective. This, however, leaves the remaining question of the fire hazard presented by the stored plastic waste.

Plastics and polymer based commodities exhibit a wide range of behavior relating to ignition and combustion which has been substantially investigated [3-8]. Plastics fall into two general categories: thermoplastics and thermoset plastics. Thermoset plastics are rigid and cannot be plastically formed even at elevated temperatures while thermoplastics will soften and melt at elevated temperatures. Thermosets do not exhibit this softening or melting during combustion and often will char when exposed to a heat source. Thermoplastics, because of their flexible nature, are commonly used as shipping and packaging materials. The vast majority of the plastic waste on ships is of the thermoplastic type which leads to a significant concern: excess melting of fuel surfaces during a fire and resultant pooling of the melt. Appendix B contains a table with material

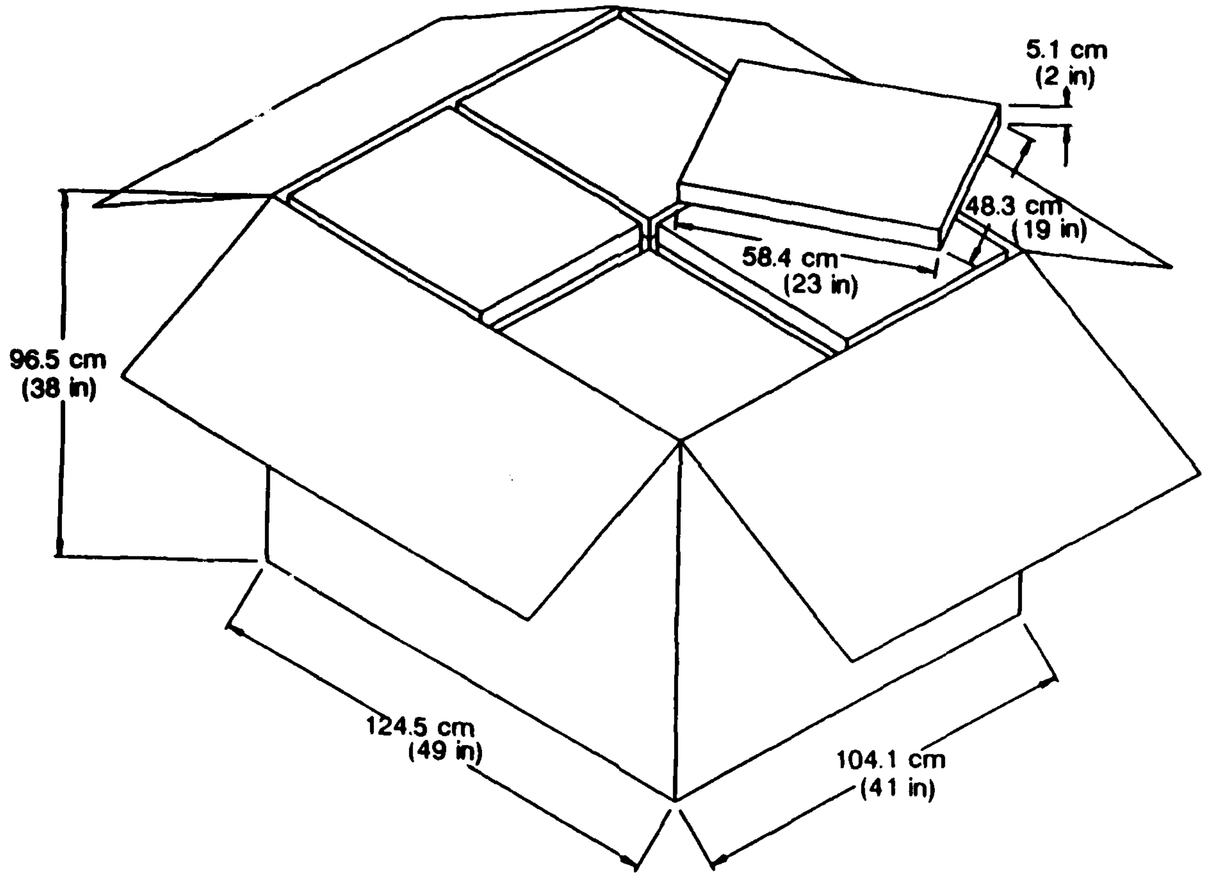

Fig. 3 - Standard Navy 1.2 m (4 ft) triwall

Table 1. Bulk versus Processed Plastic Waste Storage for ≈300 Man Ship

	1 Day		1 Week		1 Month	
	Block	Bulk	Block	Bulk	Block	Bulk
Trash by mass	36.3 kg (79.9 lb)		254 kg (558.5 lb)		1089 kg (2395.8 lb)	
Trash by volume	0.06 m^3 (2.11 ft^3)	1.68 m^3 (59.33 ft^3)	0.39 m^3 (13.77 ft^3)	11.8 m^3 (416.71 ft^3)	1.68 m^3 (59.33 ft^3)	50.4 m^3 (1,779.82 ft^3)
Trash by number of processed blocks	4		28		120	
Number of 2.4 x 3.7 m (8 x 12 ft) rooms required to store trash	0.003	0.08	0.02	0.54	0.08	2.3
Fuel load combustion in 2.4 x 3.7 m (8 x 12 ft) room	39,324 kg·cal/m^2 (14,500 BTU/ft^2)		292,896 kg·cal/m^2 (108,000 BTU/ft^2)		1,166,160 kg·cal/m^2 (430,000 BTU/ft^2)	507,144 kg·cal/m^2 (187,000 BTU/ft^2)
Fuel load: wood equivalent	9.27 kg/m^2 (1.9 lb/ft^2)		68.3 kg/m^2 (14.0 lb/ft^2)		271.46 kg/m^2 (55.6 lb/ft^2)	118.15 kg/m^2 (24.2 lb/ft^2)
Number of standard Navy 1.2 m (4 ft) triwalls	0.05	1.3	0.31	9.4	1.3	40.3

properties and performance for various thermoplastics. Regardless of the plastic waste's form, storage on the ship should be such that burning plastic melt would be prevented from running into areas where it would spread the fire, such as down drains that lead to hazardous liquids or fuel oil waste storage areas. It should also be stored so that the melt and drip will not involve other combustibles in the same space.

Fire size and rate of fire growth are issues directly related to the form and orientation of the storage of plastic waste (processed or bulk). Beyond the ignition source and air requirements, the form and storage orientation will drive the rate of fire growth and maximum potential fire size. While storage configuration is important and must be planned, taking into consideration melt and drip issues, the form of the new plastic waste will be critical to the fire growth rate. Fire growth rate is be directly related to the amount of surface area available for combustion, which is why processed bricks are more attractive than the bulk waste. Not only does the processing dramatically reduce the volume of trash, but it significantly limits the available surface area for the fire. Similarly, if the material is stored in a container such as standard Navy triwalls, the surface of the container will be a dominate factor in initial fire growth rate. The reduction in

storage volume will reduce the number of containers and thereby the extent of container surface available for fire spread and growth.

The impact of surface area on fire size can be illustrated with a simple hand calculation. A processed block measuring 0.56 m x 0.48 m x 0.05 m (22 in. x 19 in. x 2 in.) has a surface area of 0.64 m^2. Assuming the average thickness of plastic waste is 5 mm, then the available surface area from the bulk trash is 5.5 m^2. If the trash burns at an average heat release rate of 500 kW/m^2 and the processed block is suspended such that all surfaces can be fully involved, a 320 kW fire will result. Similarly, if the bulk trash was stored with all available surface area was undergoing combustion, a fire of 2.8 MW would result. A more realistic estimation would assume that the block would only have one-half of the total available surface area for combustion. This would yield a 187 kW fire for the block and a 1.4 MW fire for the bulk plastic. The duration of these fires would differ greatly as well, where the block would burn for over 20 minutes and the bulk for three minutes in the more realistic scenario.

These simple calculations illustrate that bulk trash storage creates a much more hazardous fire risk than the processed blocks and could create a situation where a fire could easily grow to flashover with a few bags or triwalls of bulk trash. On a larger scale, three weeks of trash could be processed by the PWD unit and stored as 72 blocks in a single 1.2 m (4 ft) Navy triwall. This would produce a 4.3 MW fire, assuming of course that the commodity burned as four distinct piles in the triwalls, as reflected in Fig. 3, and not melt and form a large pool fire. The bulk trash that would make 72 blocks would occupy approximately 24, 1.2 m (4 ft) Navy triwall containers. Factory Mutual Research Corporation has performed Small Array Plastic Storage Tests of palletized storage commodities [9]. Results from these tests are summarized in Appendix C. These test configurations would be comparable to ten, 1.2 m (4 ft) Navy triwalls stored in two stacks of five with 15-30 cm (6-12 in.) between the stacks. These tests, which were sprinklered, resulted in peak fire sizes anywhere from 35 to 55 MW for similar commodities. Comparable commodities resulted in 12 to 13 sprinkler heads opening to control or not control the fire. These example calculations are summarized in Table 2. Such a fire could occur with triwall boxes of bulk plastic trash stacked in some high bay space on the ship. In the case of the processed plastic blocks the number of boxes would be only one or two and the maximum rate of heat release would be controlled by the exposed surface area. As discussed above a conservative figure of merit being about 4 MW per triwall container, if that container is filled to its capacity with processed plastic blocks and then ignited. The Factory Mutual research Corporation experiments, however, do demonstrate that the combination of plastic materials in corrugated (triwall) containers is a recipe for rapid fire development if ignited.

3.1 Small-scale Ignition and Heat Release Testing

Small-scale testing of plastic waste samples produced by the plastic waste disposal unit was conducted in order to evaluate the sample's ignition and burning characteristics. These tests were performed in a cone calorimeter. The cone calorimeter uses the oxygen consumption principle to measure the heat release rate and has been

Table 2. Comparative Heat Release Rates for Plastic Waste Samples

	Total Surface Area Involved (m^2 (ft^2))	Total Mass of Plastic Waste (kg (lb))	Duration of Fire (min)	Fire Size for Total Surface Area and Average Heat Release Rate (kW (Btu/hr))
Single Suspended Block-Processed	0.64 (6.89)	9.1 (20.06)	14.2	320 (1,092,160)
Bulk Plastic Equivalent to Block	5.5 (59.20)	9.1 (20.06)	1.6	2750 (9,385,750)
Bulk Plastic Equivalent to Block @ 1/2 Total Surface Area Assuming 5 mil Average Plastic Thickness	0.37 (3.98)	9.1 (20.06)	24.3	187 (638,231)
72 Blocks in a Single 1.2 m (4 ft) Navy Triwall	8.7 (93.65)	653 (1,440)	75	4340 (14,812,420)
Ten 1.2 m (4 ft) Navy Triwalls with 27.2 kg (60 lb) of Bulk Plastic Trash Stored in Two Stacks of Five with Minimal Separation	--	272 (600)	--	35000-55000 (11,945,500-18,771,500)

well established [10-14]. The cone calorimeter test apparatus was developed as a bench scale method to measure heat release rate, gas species production rates, and other combustion related quantities. Information on the cone calorimeter have been well documented in various sources [15-17]. The cone calorimeter has been used for several applications including standard test methods [18] and ignition and heat release rates of building materials [19]. The cone calorimeter is pictorially represented in Figure 4.

3.1.1 Samples

Several samples of processed plastic waste blocks were obtained from David Taylor Research Center. These samples were created by processing actual plastic waste in the Plastic Waste Processor prototype which was developed there. The samples were chosen such that a broad spectrum of sample composition was obtained. The sample blocks were cut into 10.2 x 10.2 cm (4 x 4 in.) samples to be tested in the cone calorimeter. The samples were found to be quite stable and did not break apart during the cutting process.

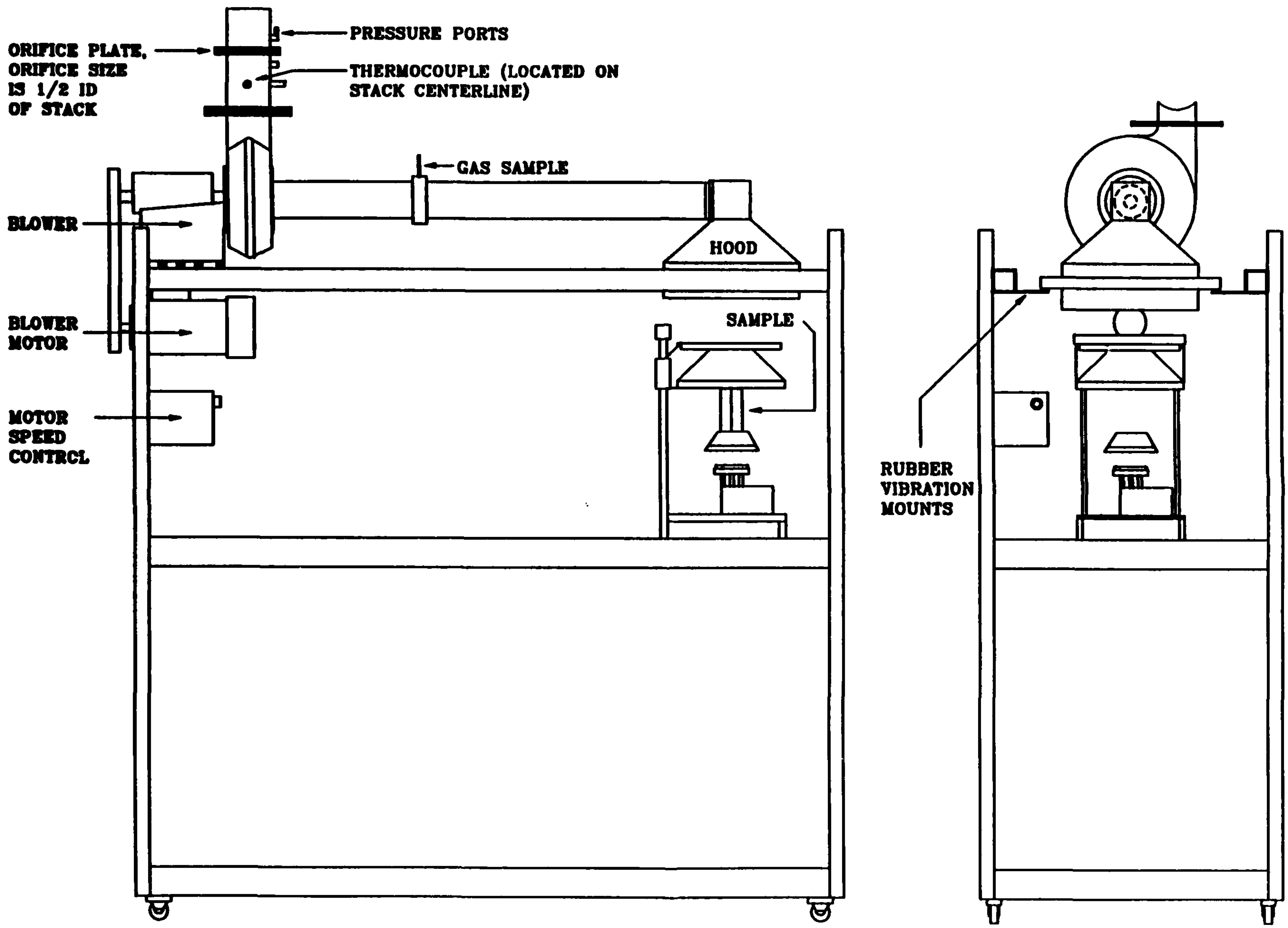

Fig. 4 - Conventional cone calorimeter

The front and back surfaces were very smooth while the edges of the block were very irregular and marked with many voids and cavities. The thickness of the sample blocks were not very uniform with a large variation from the top to the bottom.

3.1.2 Ignition

The cone calorimeter uses a cone shaped heater which exposes a 10.2 x 10.2 cm (4 x 4 in.) sample with a uniform incident radiant heat flux. Thus, a sample can be tested to determine the time to ignition at a specific incident flux. The two predominant ignition mechanisms, piloted and unpiloted ignition, can be simulated in the cone calorimeter. For piloted ignition tests, a spark source located in the pyrolysis plume initiates the onset of flaming combustion. The unpiloted ignition test uses an identical test apparatus with the spark source turned off.

Successive samples are tested in both piloted and unpiloted configurations as the incident flux applied to the sample decreases. As the incident flux is decreased, the time to ignition increases. The test series is complete when the critical incident heat flux is the smallest incident flux which will result in ignition of the sample for the particular configuration in question. Applied incident fluxes and the corresponding ignition times are presented in Figures 5 and 6 for the piloted and unpiloted configurations respectively. From these figures, the critical flux can be estimated.

Previous work [20] developed a theoretical correlation for the equilibrium surface temperature of a sample as a function of the incident flux and validated it with experimentation. This correlation and support data are presented in Figure 7, where the critical flux for piloted and unpiloted plastic waste is translated into corresponding critical surface temperatures. These ignition results are summarized in Table 3.

Since the estimated surface temperatures for unpiloted ignition (440°C) and for piloted ignition (400°C) are above the 350°C cooking temperature in the Ram Heat Chamber of the PWD unit, there is no possibility of ignition of the plastic waste during the heating cycle.

Minimum ignition flux: piloted

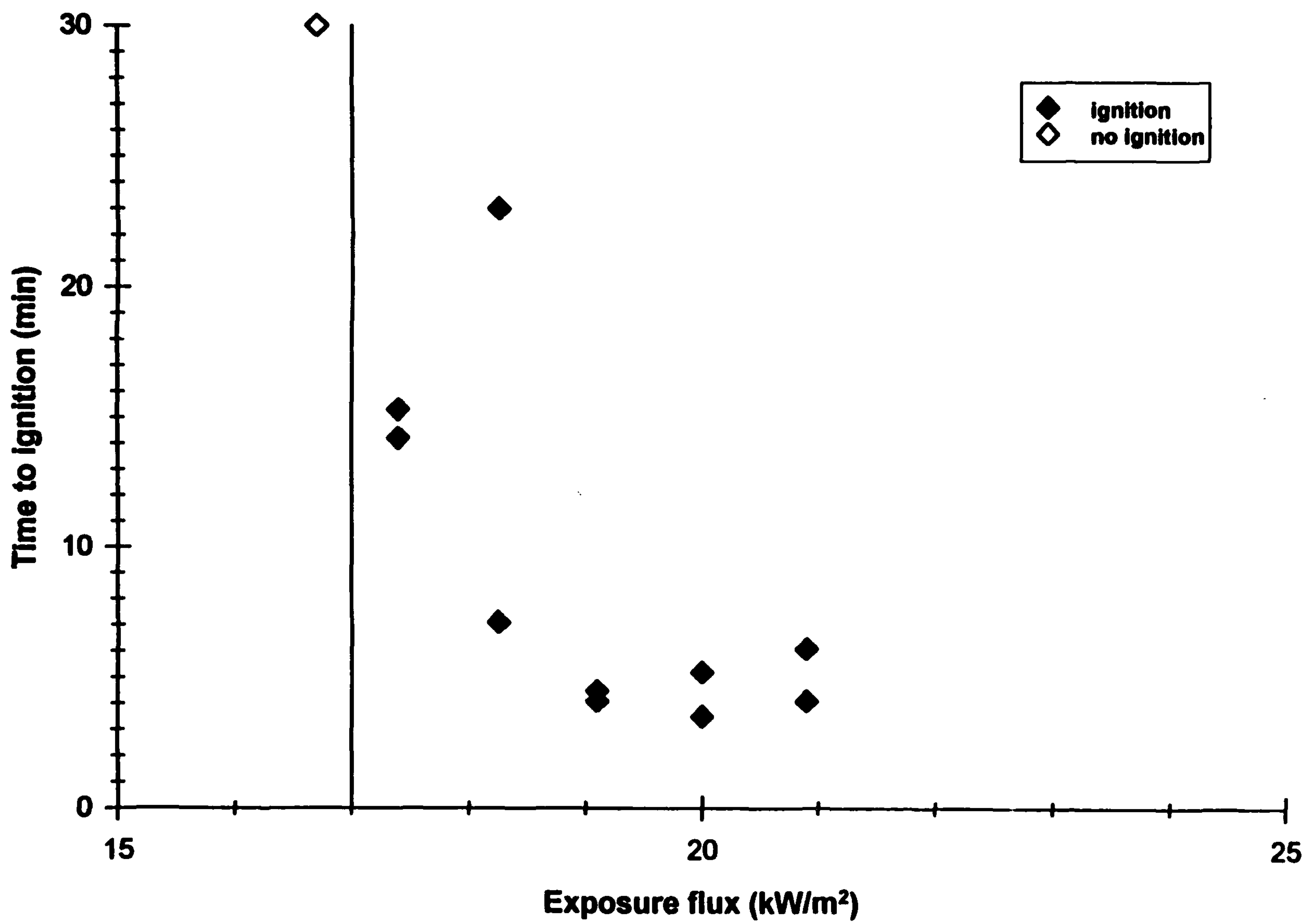

Fig. 5 - Time to ignition vs. incident flux for piloted tests

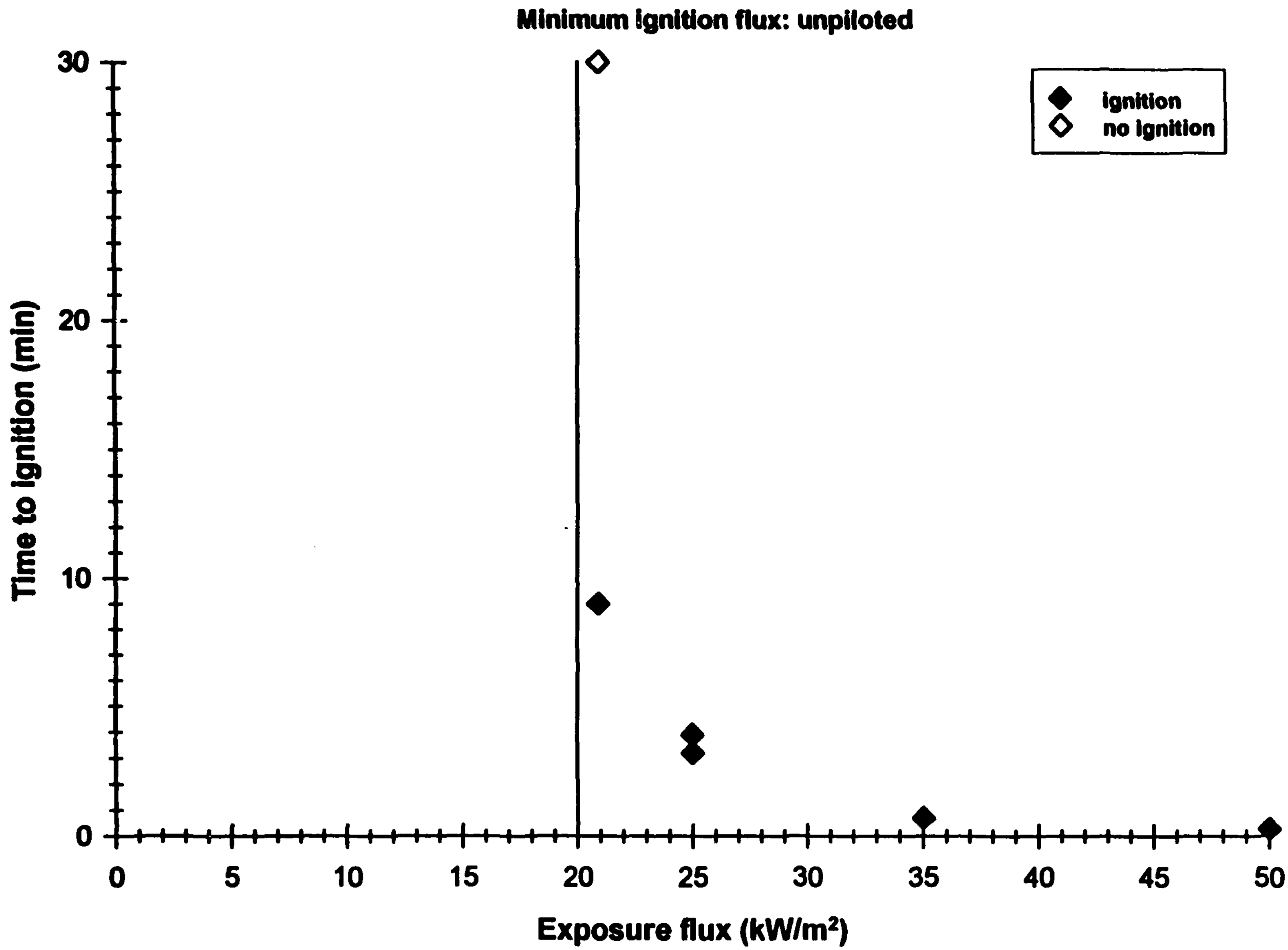

Fig. 6 - Time to ignition vs. incident flux for unpiloted tests

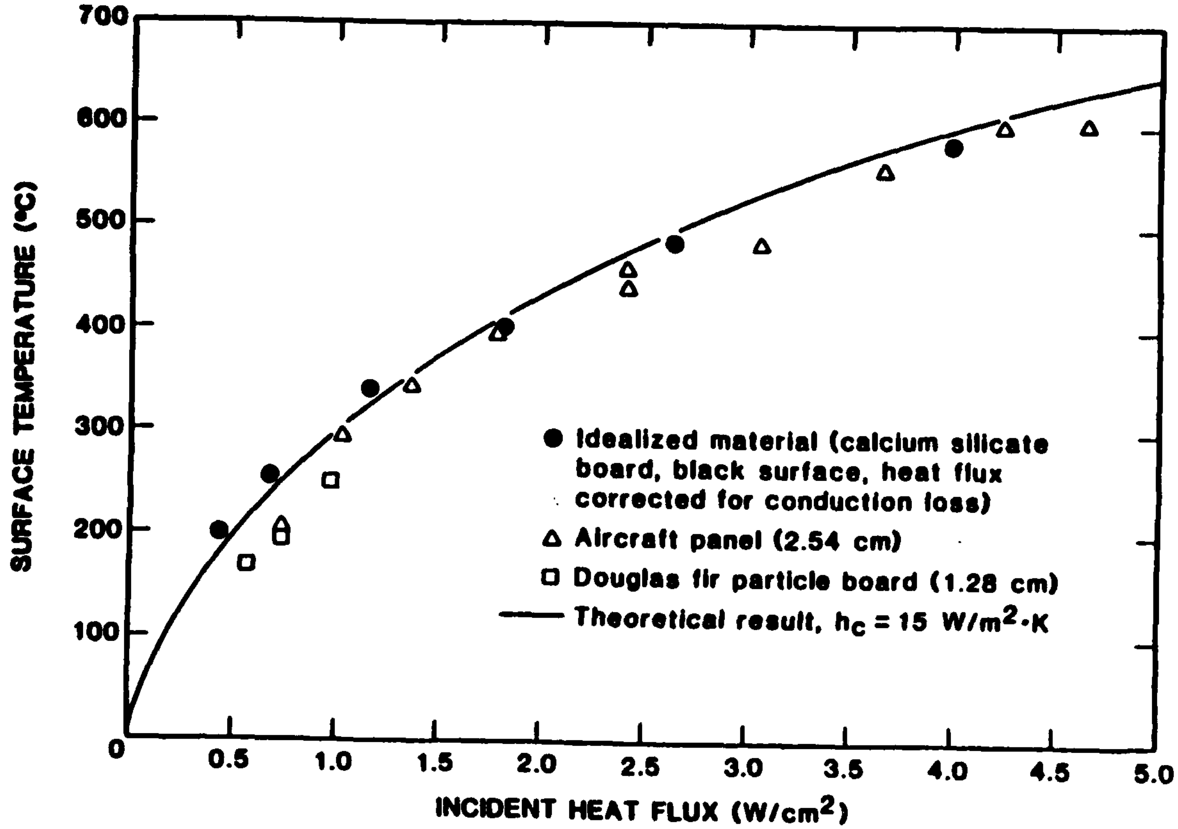

Fig. 7 - Equilibrium surface temperatures as a function of external radiant heating in the test apparatus

Table 3. Plastic Waste Samples

Ignition Mode	Minimum Incident Flux	Source Temperature	Estimated Sample Surface Temperature at Ignition
Unpiloted	20.0 kW/m^2 (1.76 $Btu/ft^2 \cdot s$)	580°C (1076°F)	440°C (824°F)
Piloted	16.5 kW/m^2 (1.45 $Btu/ft^2 \cdot s$)	540°C (1004°F)	400°C (752°F)

Minimum Incident Flux = The minimum amount of radiant energy required to achieve ignition of the sample.

Source Temperature = The temperature of the radiating cone element corresponding to a sample exposure of the "minimum incident flux"

Estimated Sample Surface Temperature at Ignition = An estimate of the surface temperature of the sample at the time of ignition based upon Figure 7.

The majority of ignition testing is performed for piloted ignition conditions, and thus, the results for the piloted ignition of the plastic waste samples can be compared with the data found in Tables 4 and 5. The estimated sample surface temperature (400°C) and minimum incident flux (16.5 kW/m^2 or 1.65 W/cm^2) for piloted ignition for plastic waste are similar to painted hardboard and glass reinforced polyester. Those materials with lower minimum incident fluxes for piloted ignition and lower estimated sample surface temperatures at ignition are more likely to ignite and therefore present a greater fire hazard. Materials with a higher ignition temperature and higher minimum heat flux for ignition are more difficult to ignite and thus pose less of a fire hazard.

3.1.3 Heat Release Rate

Ignitability is very important in determining the level of fire hazard a material presents; however, heat release rate is even more critical since a material may ignite easily, but provide a very low heat release rate. Several tests were run in the cone calorimeter to determine the heat release rate characteristics of several plastic waste samples provided by NSWC. The sample type used to investigate minimum incident heat flux for ignition was tested at 25, 50, and 75 kW/m^2 incident flux levels. Three other sample types were tested at 50 kW/m^2 incident flux, and the heat release rate as a function of time is graphically presented for each test in Appendix A. Peak heat release rate values for each test have been summarized in Table 6. The range in data at an incident flux of 50 kW/m^2 (353 - 1213 kW/m^2) is an indication of the inhomogeneity in the plastic waste material.

Table 4. Minimum Incident Flux for Piloted Ignition

Material	$q_{o,ig}{}^{b}$ (W/cm^2)
Polyurethane (S353M)	0.9
PMMA polycast, 1.59 mm	0.9
Hardboard, 6.35 mm	1.0
Carpet (acrylic)	1.0
Fiberboard, low density (S119M)	1.2
Fiber insulation board	1.4
Hardboard, 3.175 mm	1.4
Hardboard (S159M)	1.5
PMMA Type G, 1.27 cm	1.5
Asphalt shingle	1.5
GRP, 2.24 mm	1.6
Plywood, plain, 0.635 cm	1.6
Plywood, plain, 1.27 cm	1.6
Chipboard (S118M)	1.6
Douglas Fir particle board, 1.27 cm	1.6
Foam, flexible, 2.54 cm	1.6
Wood panel (S178M)	1.6
Plastic waste (processed)	1.65
Hardboard, gloss paint, 3.4 mm	1.7
Mineral wool, textile paper (S160M)	1.7
Hardboard, nitrocellulose paint	1.7
GRP, 1.14 mm	1.7
Particle board, 1.27-cm stock	1.8
Gypsum board, wall paper (S142M)	1.8
Carpet (nylon/wool blend)	1.8
Foam, rigid, 2.54 cm	2.0
Carpet #2 (wool, untreated)	2.0
Polyisocyanurate, 5.08 cm	2.1
Fiberglass shingle	2.1
Carpet #2 (wool, treated)	2.2
Carpet #1 (wool, stock)	2.3
Aircraft panel epoxy fiberite	2.8
Gypsum board, FR, 1.27 cm	2.8
Polycarbonate, 1.52 mm	3.0
Gypsum board, common, 1.27 mm	3.5
Plywood, FR, 1.27 cm	4.4
Polystyrene, 5.08 cm	4.6

Table 5. Estimated Sample Surface Temperature at Ignition (Piloted)

Material	T_{ig} (°C)
PMMA polycast, 1.59 mm	278
Polyurethane, S353M	280
Hardboard, 6.35 mm	298
Carpet (acrylic)	300
Fiberboard, low density (S119M)	330
Fiber insulation board	355
Hardboard, 3.175 mm	365
Hardboard (S159M)	372
PMMA Type G, 1.27 cm	378
Asphalt shingle	378
Douglas Fir particle board, 1.27 cm	382
Wood panel (S178M)	385
Plywood, plain, 1.27 cm	390
Chipboard (S118M)	390
Plywood, plain, 0.635 cm	390
Foam, flexible, 2.54 cm	390
GRP, 2.24 mm	390
Plastic waste (processed)	400
Mineral wool, textile paper (S160M)	400
Hardboard (gloss paint), 3.4 mm	400
Hardboard (nitrocellulose paint)	400
GRP, 1.14 mm	400
Particle board, 1.27-cm stock	412
Gypsum board, wall paper (S142M)	412
Carpet (nylon/wool blend)	412
Carpet #2 (wool, untreated)	435
Foam, rigid, 2.54 cm	435
Polyisocyanurate, 5.08 cm	445
Fiberglass shingle	445
Carpet #2 (wool, treated)	455
Carpet #1 (wool, stock)	465
Aircraft panel epoxy fiberite	505
Gypsum board, FR, 1.27 cm	510
Polycarbonate, 1.52 mm	528
Gypsum board, common, 1.27 cm	565
Plywood, FR (1.27 cm)	620
Polystyrene (5.08 cm)	630

Table 6. Plastic Waste Measured Peak Heat Release Rates

Sample Type	Incident Flux (kW/m^2)	Peak Heat Release Rate (kW/m^2)
A	25	360
A	50	869
A	50	1213
B	50	674
B	50	747
C	50	353
C	50	518
D	50	946
D	50	1069
A	75	1007

The average peak heat release rate[1] for all samples at 50 kW/m^2 is 799 kW/m^2. This can be compared with previous work done on the heat release rates of plastic materials at 40 kW/m^2 incident flux [21] as summarized in Table 7. The average peak heat release rate of the processed plastic waste is roughly similar to polyurethane and PMMA.

3.1.4 Observations

There were a few noteworthy trends observed during the testing of the plastic waste processed blocks.

1. During the low incident flux ignition tests,

   a. Quite often the top surface of the sample formed a very thin layer of char and puffed up which brought the charred surface closer to the radiant source which increases the incident flux level; and

[1] The deviation in heat release rate for an incident flux of 50 kW/m^2 is approximately plus or minus 50% of the average heat release rate. Since the content of the material in the individual blocks tested varied according to the mix of specific plastic materials processed in producing the individual block it is not unexpected that the heat release rate would vary between blocks or even among samples taken from a single block.

Table 7. Peak Heat Release Rates for Materials
(Incident Flux = 40 kW/m^2)

Material	Peak Heat Release Rate
PTFE	13
Flexible vinyl thermoplastic	43
Flexible vinyl thermoplastic	64
Flexible vinyl thermoplastic	77
PVC-chlorinated	84
Flexible vinyl thermoplastic	87
PVC (wire and cable) with FR	92
PVC (rigid) with low smoke	111
PVC (wire and cable) with minimal FR	142
PVC (wire and cable) with no FR	167
PVC (rigid) with impact mod	175
Kydex; FR acrylic panel	176
PVC (rigid) with extrusion	183
Polyethylene copolymer	192
Douglas Fire wood	221
Thermoplastic polyurethane with FR	221
PVC (flexible)	237
Polyphenylene oxide/polystyrene	265
Polyphenylene oxide/polystyrene with 20% fiberglass	276
ABS with PVC additive	291
Polystyrene with FR	334
Polyformaldehyde	360
ABS with FR	402
Polycarbonate	420
Polycarbonate	429
PET	534
PMMA	665
Polyurethane	710
Plastic waste (processed) @ 50 kW/m^2	799
ABS	944
Polystyrene	1101
Nylon 6,6	1313
Polybutylene terephthalate	1313
Polyethylene	1408
Polypropylene	1509

b. Also, often there would be smoke spots on the exposed surface which would be glowing as a red light or ember and which were ascribed to foreign material and surface incongruities that were hotter than the rest of the surface. Ignition appeared to be more likely when there was a portion of the sample that formed a liquid "pool" of melt. The thin layer of char seemed to help in resisting ignition.

2. Samples exposed to high fluxes ignited quickly before the top surface had any significant char. This occurred as the top surface rapidly melted and quickly pyrolyzed.

3. Some samples had a plastic "frizz" on the surface as a result of being removed from the Plastic Waste Processor while the surfaces were still melted. This facilitated rapid ignition because the fine strands of plastic melted and vaporized before a char layer could form, igniting the surface.

4. Samples exposed to high incident heat fluxes underwent significant melting and even ran and dripped over the edge of the sample holder in some cases.

5. The samples did not delaminate or demonstrate an increase in the burning area during the tests.

3.2 Mathematical Modeling

The mathematical compartment fire model FIRE SIMULATOR [22] was used to place the preceding information in context of a potential fire that might occur if processed plastic waste were stored in triwalls in a plastic waste processing compartment or other compartment of similar size. The compartment envisioned is 3.05 m (10 ft) by 4.6 m (15 ft) by 2.1 m (7 ft) high. There is a door that has a raised sill, 0.12 m (4.8 in.) above the deck and an opening height 2.01 m (80 in.) above the deck. If the door is wide open the width of the opening is 0.9 m (36 in.). There is a ventilation system taking air from the ceiling level capable of 4 air changes per hour. There is a supply for this vent that will provide the 4 air changes per hour even if the door is tightly closed. The fire is assumed to follow a growth curve that increases with the square of time such that the fire increases in size with the square of the time since ignition, reaching 1 MW in 150 seconds and continuing at this same rate of increase to 4 MW. This is referred to as a fast t-squared fire. For comparison a second t-squared fire growth curve reaching 1 MW in 600 seconds was also considered. This is referred to as a slow t-squared fire.

The response of smoke detectors and sprinklers, each located 2.74 m (9 ft) from the position of the fire was also evaluated. Runs of the model were conducted with the door open, the door closed but with a 0.005 m (1/8 in.) crack at both the hinge and latch side, and the door closed and sealed so that no gap occurred. The runs were conducted with and without the 4 air changes per hour. Table 8 lists the seven scenarios

run. The RTI or Response Time Index is a measure of the sensitivity of the sprinkler head's thermal actuating element.

Table 8. Fire Scenarios used in FIRE SIMULATOR Runs

Case No.	Fire	Door Width	AC/hr	RTI (m/s)
1	FAST	0.01 m (1/2 in.)	4	27.6
2	FAST	0.01 m	0	27.6
3	FAST	0	0	27.6
4	FAST	O.9 m	4	27.6
5	FAST	0	4	27.6
6	SLOW	0.1 m	4	27.6
7	SLOW	0.1 m	4	220.83

The significant results of the runs listed in Table 8 are tabulated in Table 9.

Table 9. Significant FIRE SIMULATOR Results

Case No.	Smoke Detector			Sprinkler			Flashover	
	Actuation Time (s)	Fire Size at Actuation (kW)	Layer Temperature at Actuation (°C)	Actuation Time (s)	Fire Size at Actuation (kW)	Layer Temperature at Actuation (°C)	Time to Flashover (s)	Fire Size at Flashover (kW)
1	18	15	30	61	173	106	128	763
2	19	17	30	61	173	106	128	763
3	19	17	30	61	173	106	NO	NO[2]
4	18	15	30	63	185	102	225	2359
5	18	15	30	61	173	162	131	800
6	60	10	29	156	72	80	361	381
7	60	10	29	241	170	200	361	381

[2] Flaming stopped at 190 seconds at 547°C due to oxygen starvation based on smoke to floor and oxygen level reduced to 10%.

The temperature, interface levels, and oxygen concentrations in the smoke histories for Cases 1, 2, 3, and 4 are presented in Figures 8, 9, and 10.

3.2.1 Results Without Sprinkler Protection

As can be seen from Table 9 and Figures 8, 9 and 10, it is only in the Case 3 where the compartment is sealed tight that the fire is effectively smothered. Such tight sealing is unlikely in actual practice unless the compartment involved is specially designed for tightness. At the opposite end of the spectrum, Case 4 demonstrates the potential of a fully involved flashed over fire if the door is open and the fire is not suppressed. Both Cases 1 and 2 show that the fire will bank down if the available air is limited, i.e., supplied by the ventilation system or drawn in through the leakage around the door. In these cases, however, it is expected that major quantities of unburned hydrocarbons would have accumulated in the smoke and there is a distinct potential of flare-up or even backdraft explosion if the door is opened for fire attack or other purposes once the fire has passed the point of the peaks shown in the figures.

It is possible that once ignited, fire could develop to flashover before any manual fire attack with either fire extinguishers or hose streams could be initiate. In such case, if the compartment door were closed and kept closed, but some air supply for combustion continued to be available through leakage or ventilation system, the temperature level would undergo a brief excursion, indicated by FIRE SIMULATOR as peaking in the range of 600°C and remaining above 300°C for about 2 minutes, then leveling off to lower temperatures depending on the amount of air available for combustion. It is possible that this brief temperature excursion could do some limited damage to the structural strength and related fire containment abilities of aluminum but not to steel bulkheads. It would be expected that the fire could be contained to the room of origin with minimum effort. Actual suppression could be difficult involving some danger to the firefighters when they opened the door to start suppression activities. If the door were open and remained, so flashover is very possible with the resultant flow or either flame or a potentially lethal "corridor" wave front containing high concentrations or carbon monoxide, and carbon dioxide and little or no oxygen. The total impact and fire duration would depend on the total of the plastic storage plus such other combustible materials present in the space and the effectiveness of manual firefighting efforts.

3.2.2 Results With Sprinkler Protection

The FIRE SIMULATOR results indicate that in all cases sprinklers will activate prior to any significant destructive burning with the door in either an open or closed position. While quick response heads would enhance the suppression capabilities by operating at lower rate of heat release, standard heads would also operate before the development of any significant hazard. A manually operated sprinkler system could also suppress the fire, if the water supply were adequate, but not until greater damage occurred. If activation was significantly delayed and the door were open, it is quite possible that flashover would occur with resultant flame spread into the passageway.

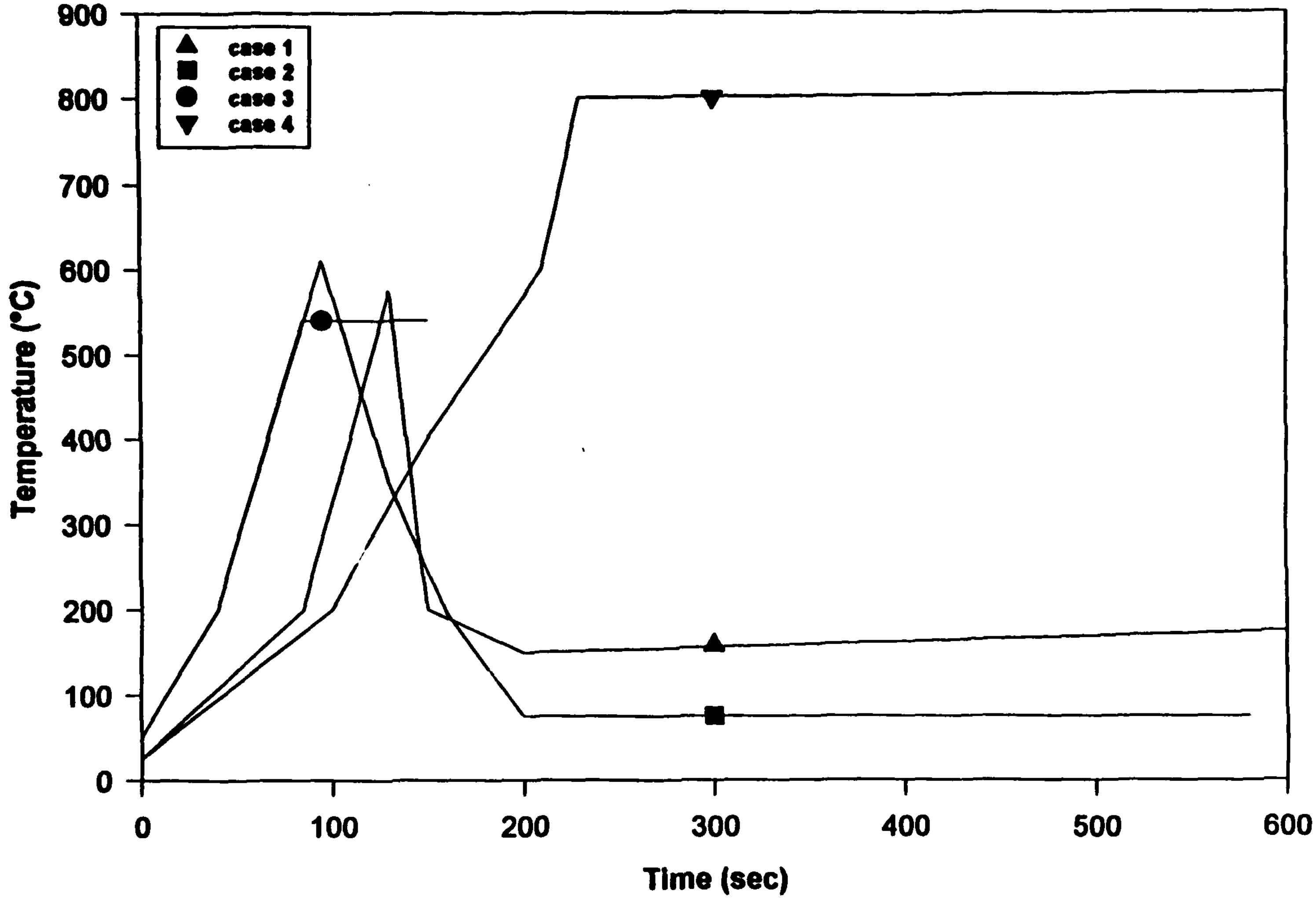

Fig. 8 - Smoke layer temperatures as predicted by FIRE SIMULATOR

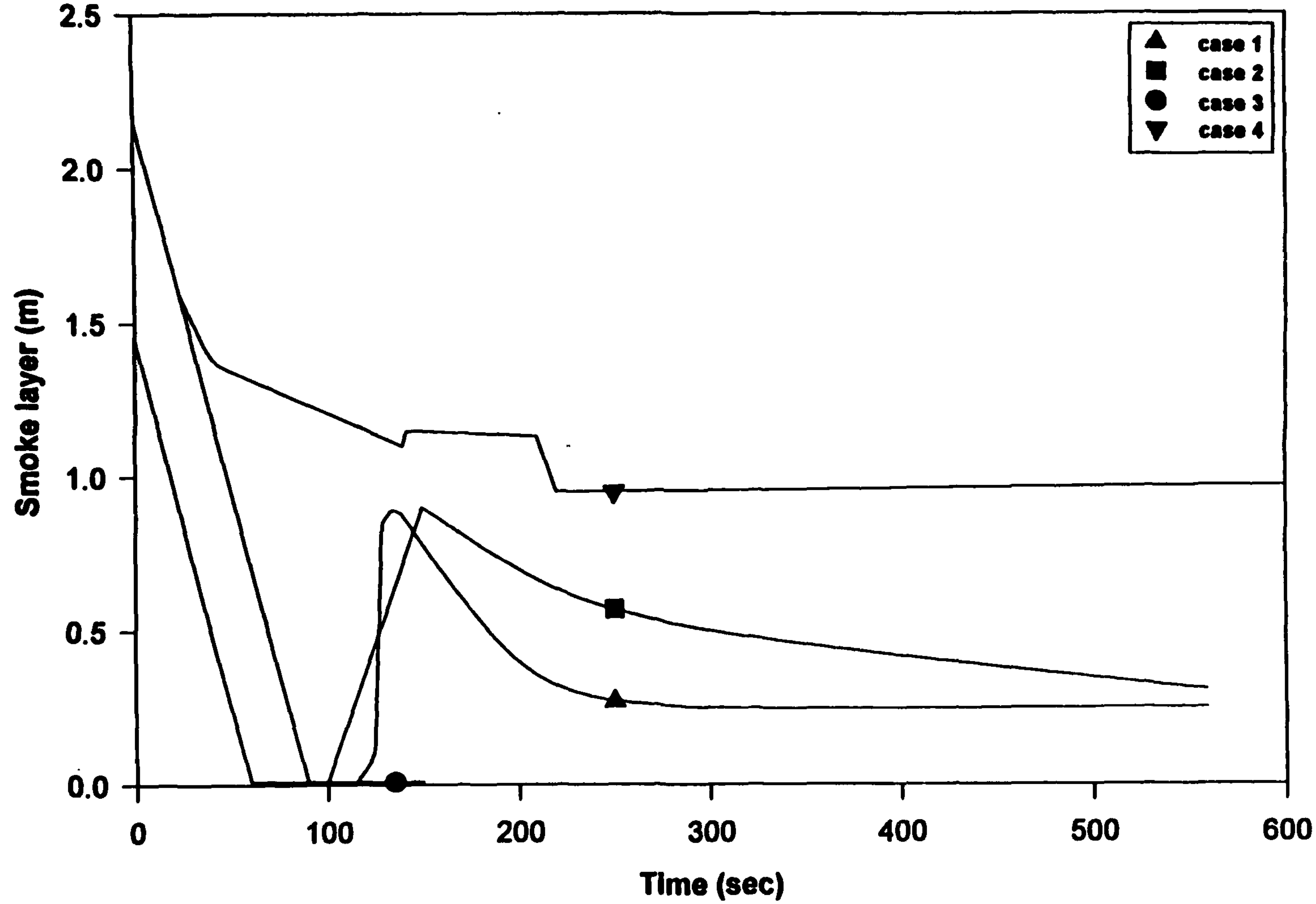

Fig. 9 - Smoke layer level as predicted by FIRE SIMULATOR

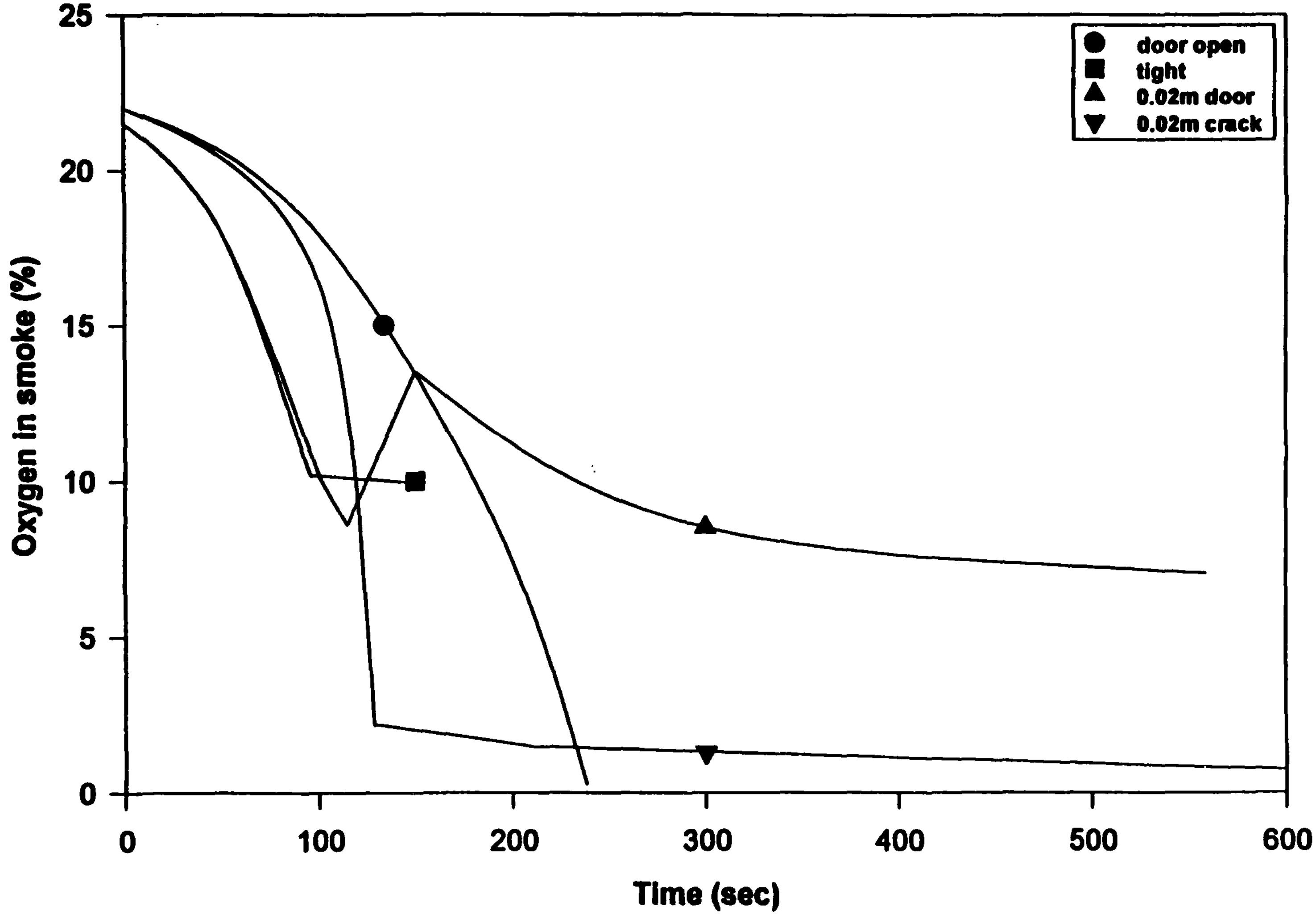

Fig. 10 - Oxygen concentration in smoke layer as predicted by FIRE SIMULATOR

It is highly probable that a sprinkler system designed to provide a discharge density for Ordinary Hazard (Group 2) commodities in a space the size of the plastic waste preparation compartment would be adequate. There is no indication in either full-scale test data or standards that plastic materials in this form stored to two containers in height cannot be effectively controlled by such a sprinkler density. The relatively small dimensions of the space effectively limit the number of heads that can operate. Problems associated with sprinkler effectiveness might be expected to occur in larger area spaces (>2000 ft^2) and with high (>12 ft) storage heights. Such warehouse type storage quantities and arrangements are probably not relevant to this hazard analysis. If further evidence of sprinkler efficacy for these materials is required, two approaches to such testing are available. The simplest is to conduct a mock-up test in a space simulating a typical plastic waste processing or storage compartment, install sprinkler protection with the maximum potential spacing and with the minimum water supply that meets the base NAVSEA design criteria, load the space with the maximum amount of processed plastic in triwall containers expected to be experienced on shipboard and conduct a burn test. Such a test will both challenge the system and prove the design. It will not however give information of the performance if the storage is in some other location, the water supply would be less than the standard requirement, or other variation from the specific scenario and configuration tested. It is possible to obtain more generic information that can be generalized to broader use by using a large combustion calorimeter, such at the one at the Chesapeake Bay Division of NRL, and measuring the actual burning rates of the processed plastic waste in triwall containers first, without the addition of water, and then in successive test with the application of carefully controlled rates of water application.

4.0 CONCLUSIONS

Plastic waste presents problems common to the storage of general plastic commodities, in both bulk and processed forms. It has been demonstrated through previously described calculations and tests that the storage form and configuration are significant factors in determining the fire hazard associated with plastic waste. Uncompressed bulk plastic waste storage presents a higher fire hazard than the processed blocks. In addition to reducing the fire hazard, the processed plastic waste blocks also alleviate other odor and sanitation problems associated with food contamination in the bulk plastic waste. The analysis conducted substantiates the need for sprinkler protection where plastic waste stored, regardless of whether it is in the bulk or processed block form.

Small scale testing which was performed to determine ignitability and heat release rate performance of the processed plastic waste yielded no real surprises. The plastic waste samples performed as one would expect typical thermoplastics to behave. The test results dispelled any concerns for ignition of the plastic waste under processing in the heat/melt chamber.

While the storage of plastic waste in the block form does provide a distinct reduction on fire hazard and is highly recommended as the better approach if plastic

waste is to be kept on board, the residual hazard can still be considerable and needs to be safeguarded against.

The following are specific conclusions with brief explanations.

1. The processed plastic waste blocks burn with a heat release rate similar to that of polyurethane and PMMA.

2. Unpiloted ignition of the processed plastic waste blocks is estimated from experimental results to occur 440°C (824°F) which is much higher than the maximum temperature the plastic waste would reach during processing of 177°C (350°F). Thus, there is not a danger of normal processing igniting generic plastic waste.

3. The Plastic Waste Disposal processed blocks of plastic are preferred over bulk plastic if plastic waste is to be stored on board the ship.

4. While the plastic blocks present far less of a fire hazard than the bulk plastic waste the potential of a serious fire from their storage still exists and needs protection.

5. The best protection for the type of residual hazard resulting from the storage of processed plastic waste is the combination of sprinkler protection and limiting the stacking of any such storage to not more than two triwall boxes high. If higher stacking becomes essential, an increased rate of water delivery from the sprinklers will be needed. Because of the expected rapid rate of fire dévelopment on the triwall containers quick response sprinkler heads are recommended to attack the fire at the earliest moment when the rate of heat release is still relatively low thereby optimizing the capabilities of the water supply. At a minimum, the sprinkler system should include quick response sprinklers designed for Ordinary Group 2 for the following reasons:

   a. The storage of plastic is limited to no greater than 8 ft high;

   b. These cannot be more than 1 or 2 rows of plastic storage by the geometry of the space;

   c. Ordinary Group 2 covers fast-growing fires with up to 12 ft storage height;

   d. Extra Hazard refers to <u>storage</u> of Group A plastics. This implies that the height of the storage can be greater and the size of the space can be larger;

   e. A member of the NFPA 13 Committee independently evaluated the hazard and recommended Ordinary Group 2;

f. Sprinkler protection for similar plastics (polyethylene beads and cardboard drums) in 12 ft high spaces is typically done as Ordinary Group 2; and

g. The compartment involved is relatively small; there is no risk that the fire can grow beyond the demand area for which the sprinkler system is sized.

If any of these conditions do not apply for a particular installation, the classification needs to be modified.

6. If it is elected to base fire safety on an arrangement that does not include sprinklers, it is very important that self (or automatic) closures be installed on the doors leading to the storage area of the processed plastic waste. This procedure can contain the fire to the storage area if the plastic waste was involved in a fire. It is probable, however, that there will be enough air leakage into the storage room so that fire will continue in that space until the fuel involved is consumed or the fire is manually extinguished.

7. Particularly if the space is not sprinkler protected, the plastic waste storage area should be properly diked to prevent any melted plastic from flowing into drains or under doors as is done for flammable liquids storage. This is due to the high concentration of thermoplastics found in the plastic waste which melt, drip, and run when exposed to heat and flame. The dike will also contain the melt limiting the size of any resulting pool fire.

8. It is recommended that a series of tests be made to confirm the fire hazard analysis made in this report and to determine the best design parameters for automatic sprinkler protection of plastic waste storage and to verify the design.

9. Screening procedures for the plastic waste to be processed should be implemented to avoid the inclusion of materials which could enhance the possibility of a fire, such as plastic containers holding flammable liquid remnants.

10. The small-scale cone calorimeter testing of the plastic waste samples was an inexpensive and realistic method to develop data on the processed plastic. Specifically, the testing provided valuable data on ignition sensitivity and heat release rate, which enabled the comparison between plastic waste and more typical plastic commodities. It demonstrated the material's propensity for melting and reduced concern over "delamination." The data developed further permitted a quantitative fire hazard assessment of the material.

5.0 RECOMMENDATIONS

Based on the hazard analysis described in this report, the following recommendations are made relative to the design and installation of shipboard plastic waste processors.

1. Warning placards should be posted at each area where plastic waste is to be stored, either processed or unprocessed. Warning placards should also be posted on the Plastic Waste Processor. The warning placards should prohibit the storage and processing of hazardous materials, including aerosol containers and butane lighters, that may contribute to the ignition of plastic waste. Also, lighted tobacco products should be prohibited at all times in the PWP space and plastic storage areas.

2. An automatic sprinkler system utilizing 165°F or 212°F quick response heads designed and installed in accordance with NFPA 13 for an Ordinary Hazard Group 2 occupancy should be provided.

3. Provisions should be made to insure that any melted material cannot flow freely beyond the processor or compartment.

4. The impact of deflagrations or explosions in the processor resulting from aerosol products or flammable liquids inadvertently placed in the waste stream needs to be evaluated.

5. Self-closing doors should be provided if

    a. automatic sprinkler protection is not provided <u>or</u>

    b. automatic sprinkler protection for the space is provided, but there are no sprinklers in the adjoining passageway.

    The provision of self-closing doors will decrease the level of fire risk in all cases.

6. Portable fire extinguishers, preferably stored pressure 2.5 gallon AFFF extinguishers, should be provided inside the compartment.

7. Full-scale testing should be conducted to verify the fire hazard analysis performed and to optimize the sprinkler system design criteria.

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Appendix A

Cone Calorimeter Test Data: Heat Release Rates

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 25 kW/m² INCIDENT FLUX

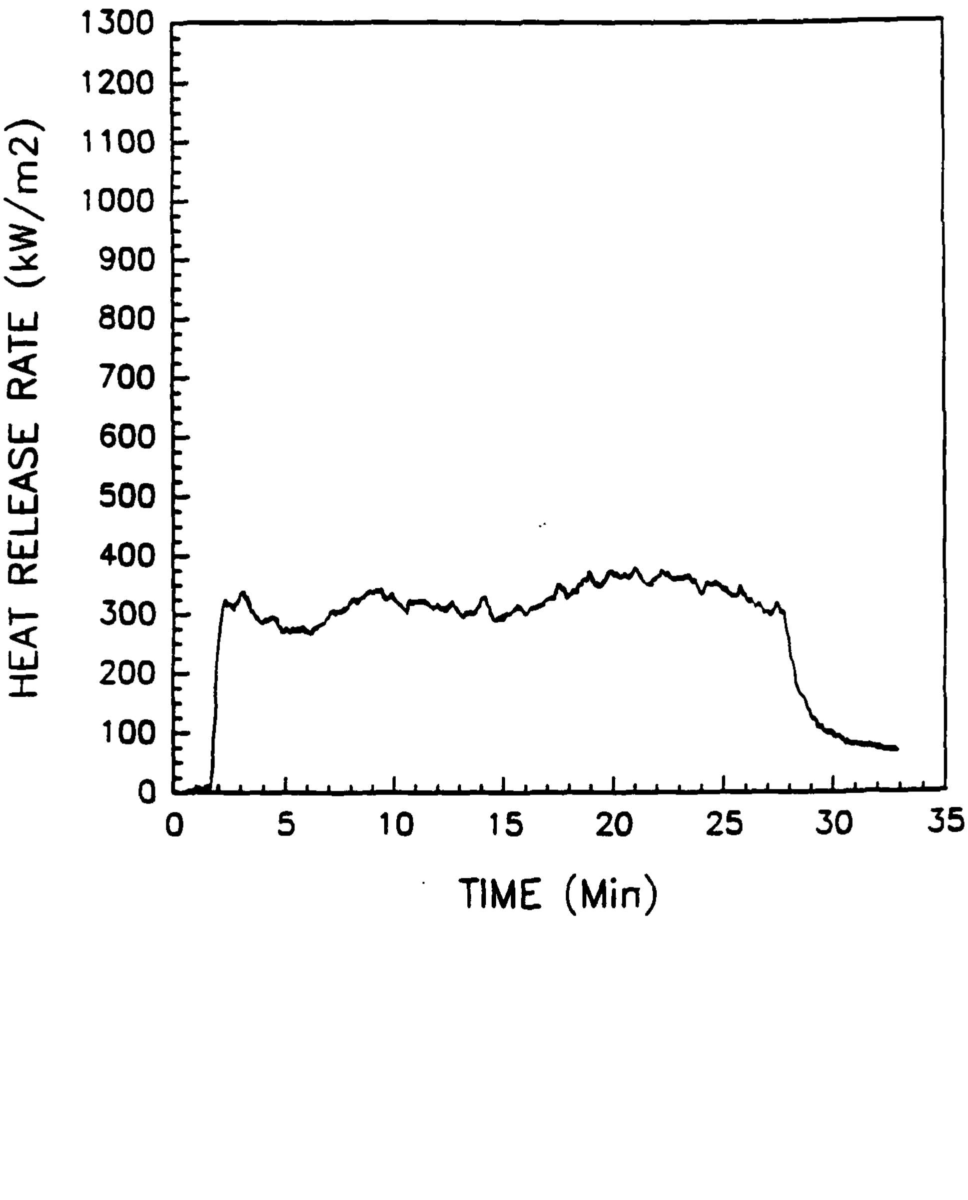

Fig. A-1

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 25 kW/m² INCIDENT FLUX

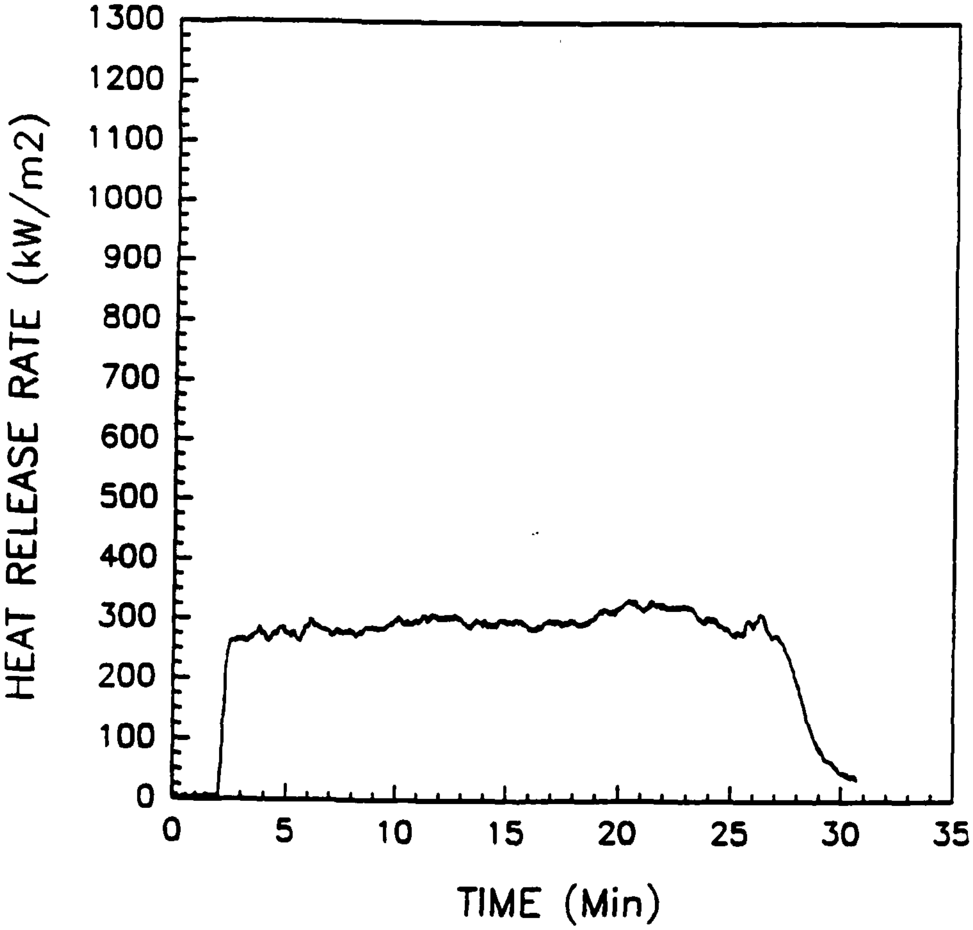

Fig. A-2

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 50 kW/m² INCIDENT FLUX

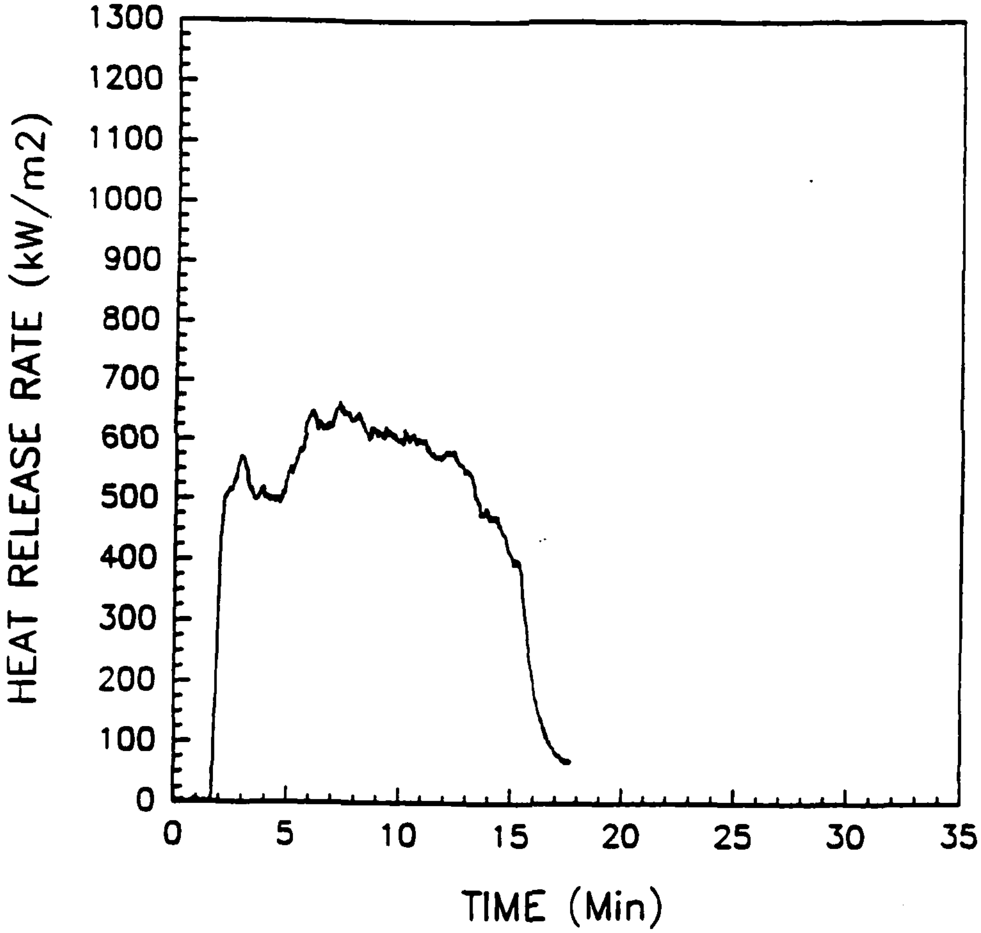

Fig. A-3

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 50 kW/m² INCIDENT FLUX

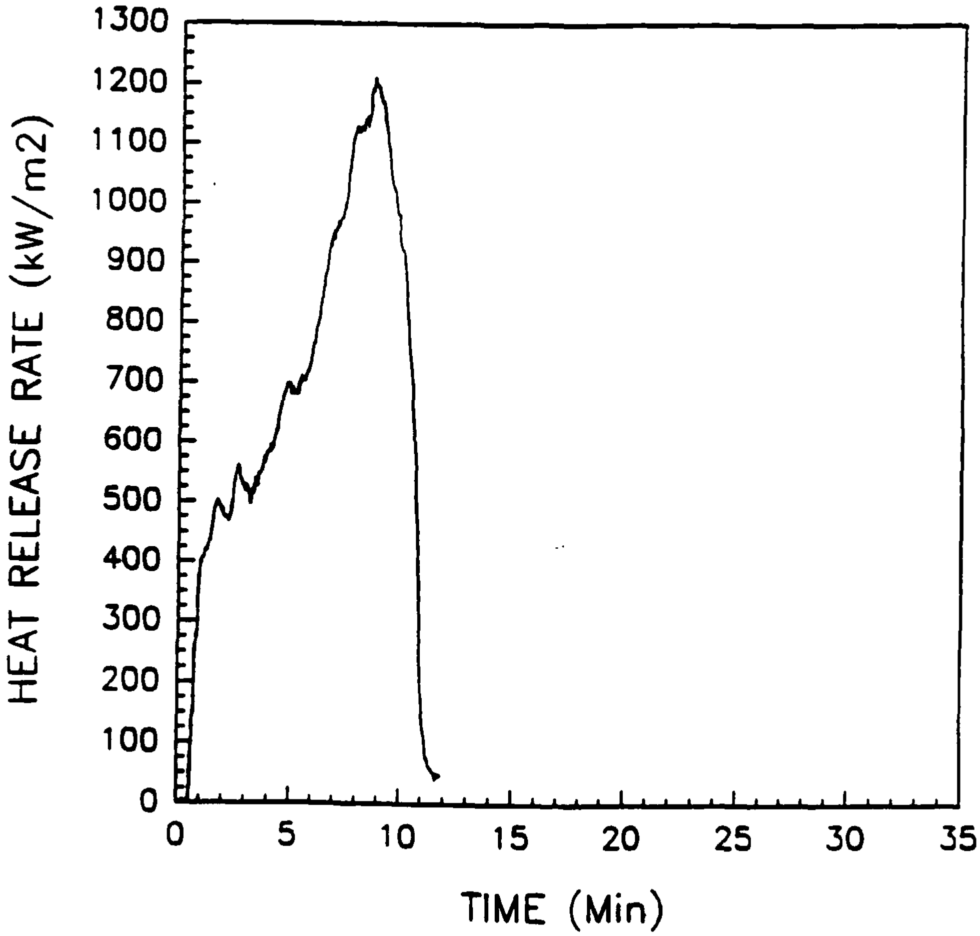

Fig. A-4

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 50 kW/m² INCIDENT FLUX

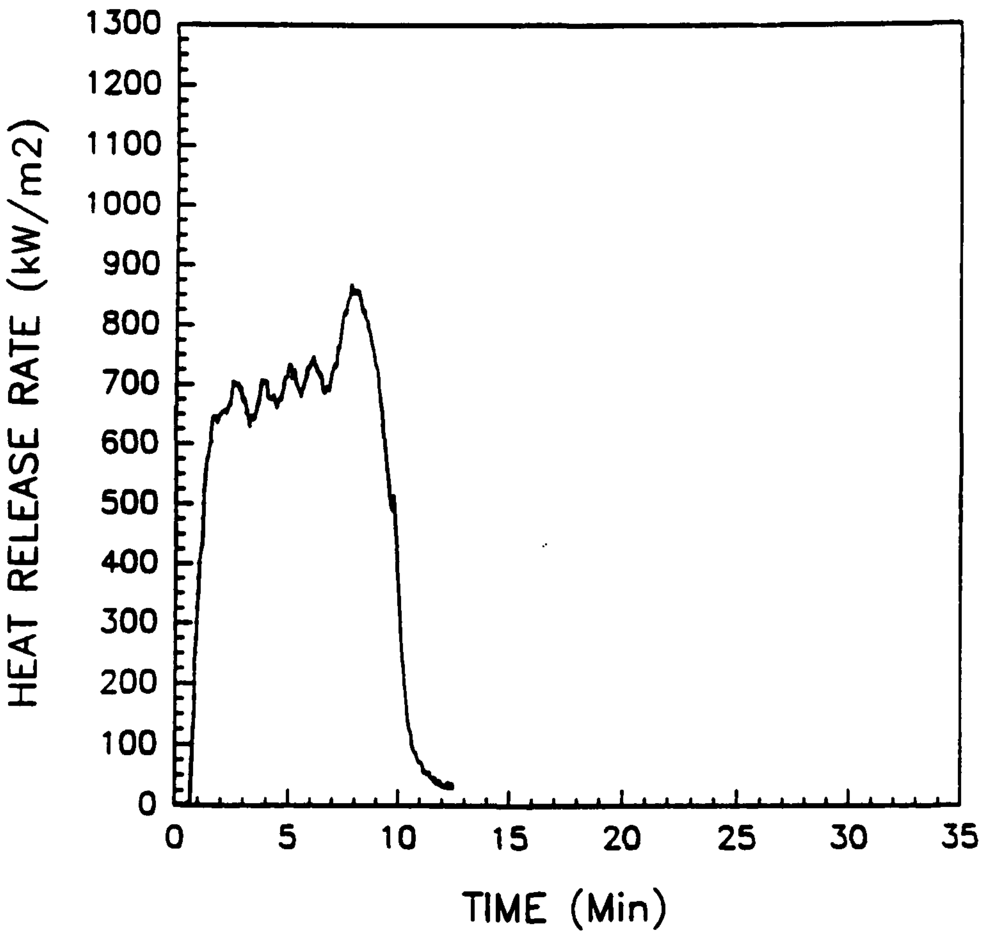

Fig. A-5

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE B - 50 kW/m² INCIDENT FLUX

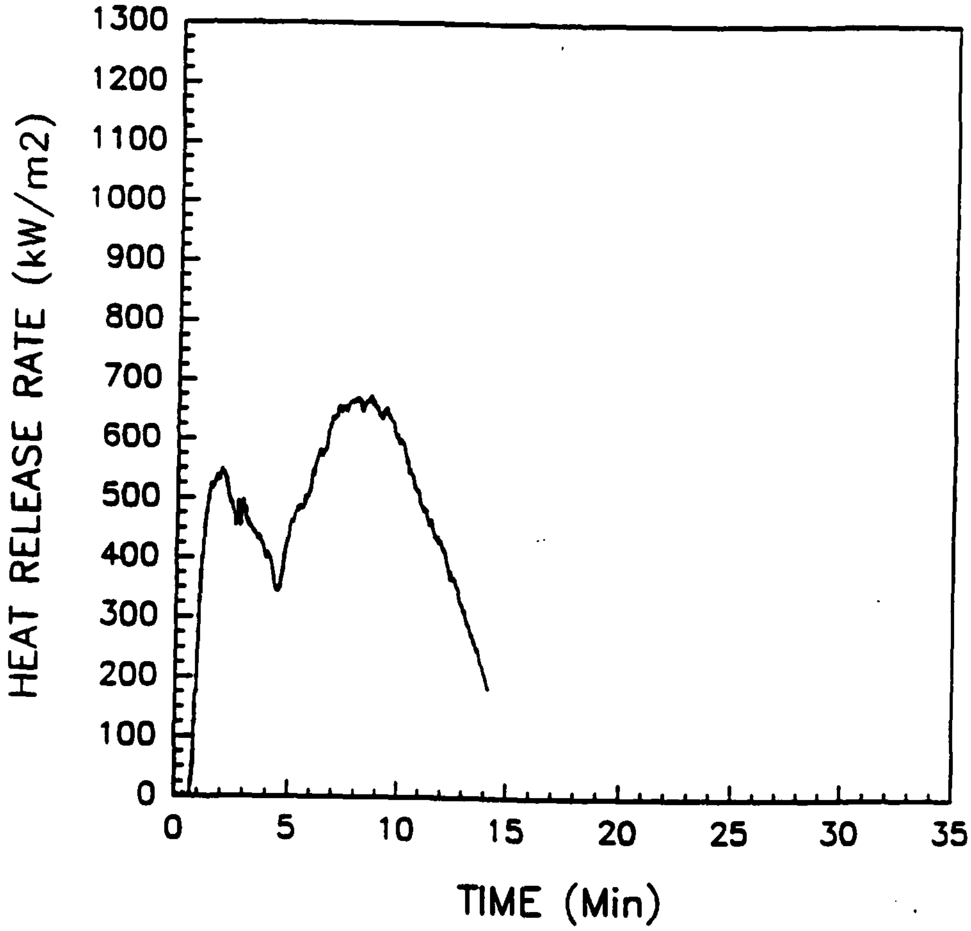

Fig. A-6

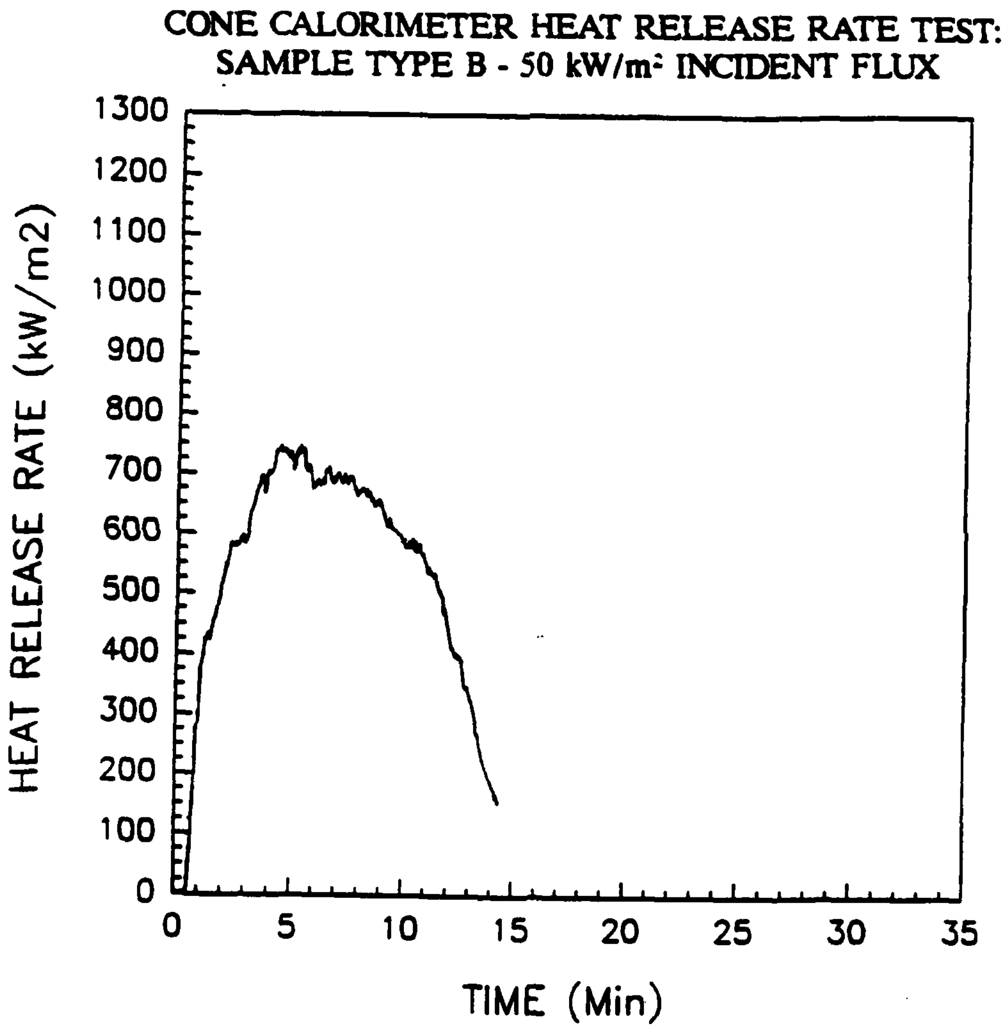
CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE B - 50 kW/m² INCIDENT FLUX
HEAT RELEASE RATE (kW/m2)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
TIME (Min)

Fig. A-7

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE C - 50 kW/m² INCIDENT FLUX

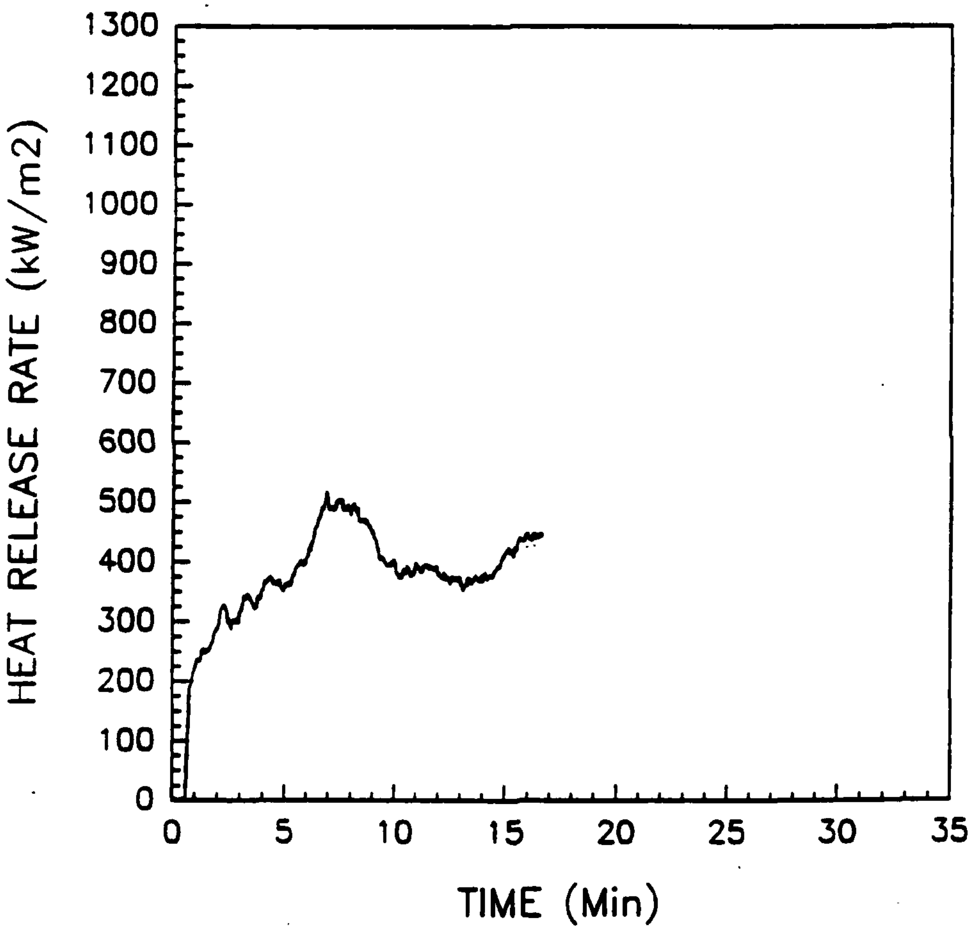

Fig. A-8

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE C - 50 kW/m² INCIDENT FLUX

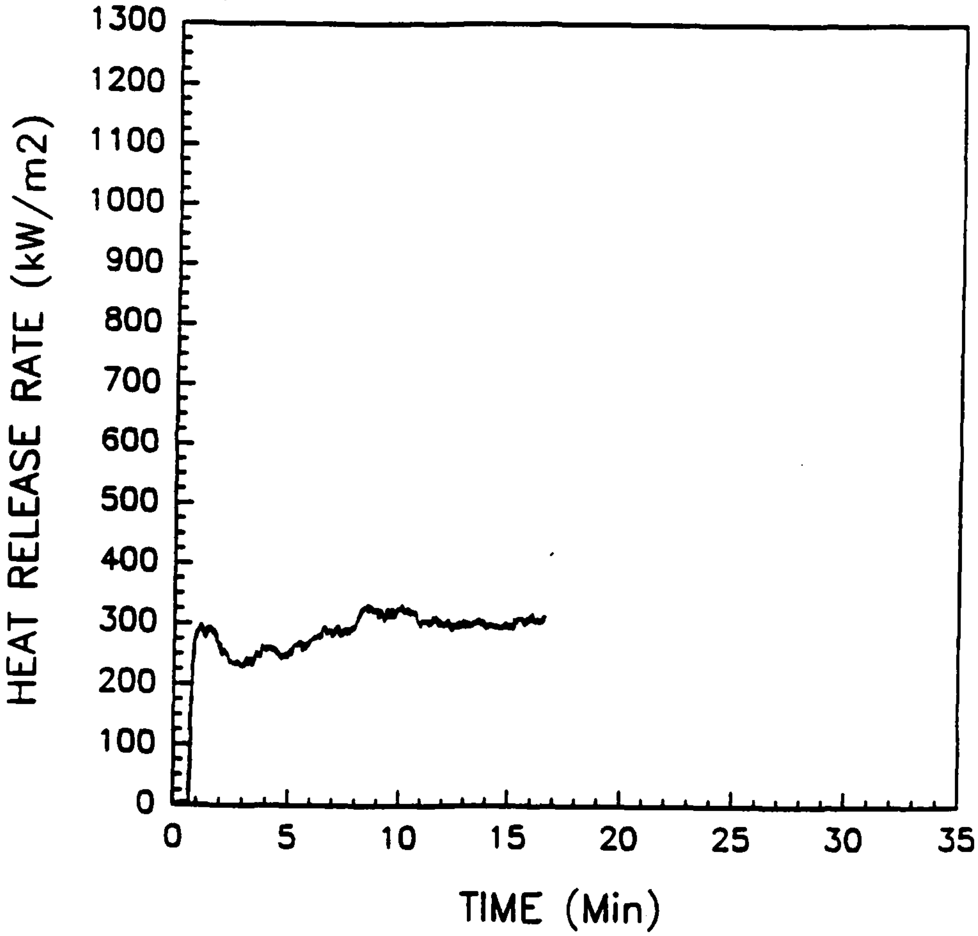

Fig. A-9

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE D - 50 kW/m² INCIDENT FLUX

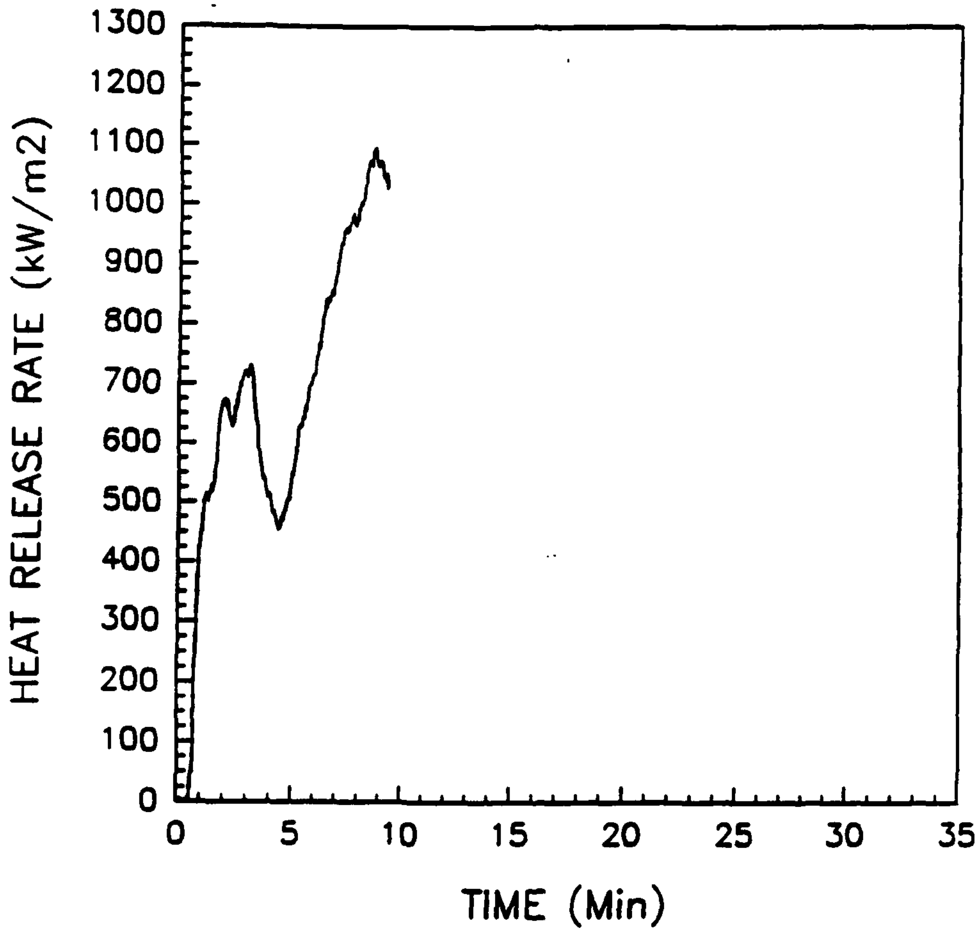

Fig. A-10

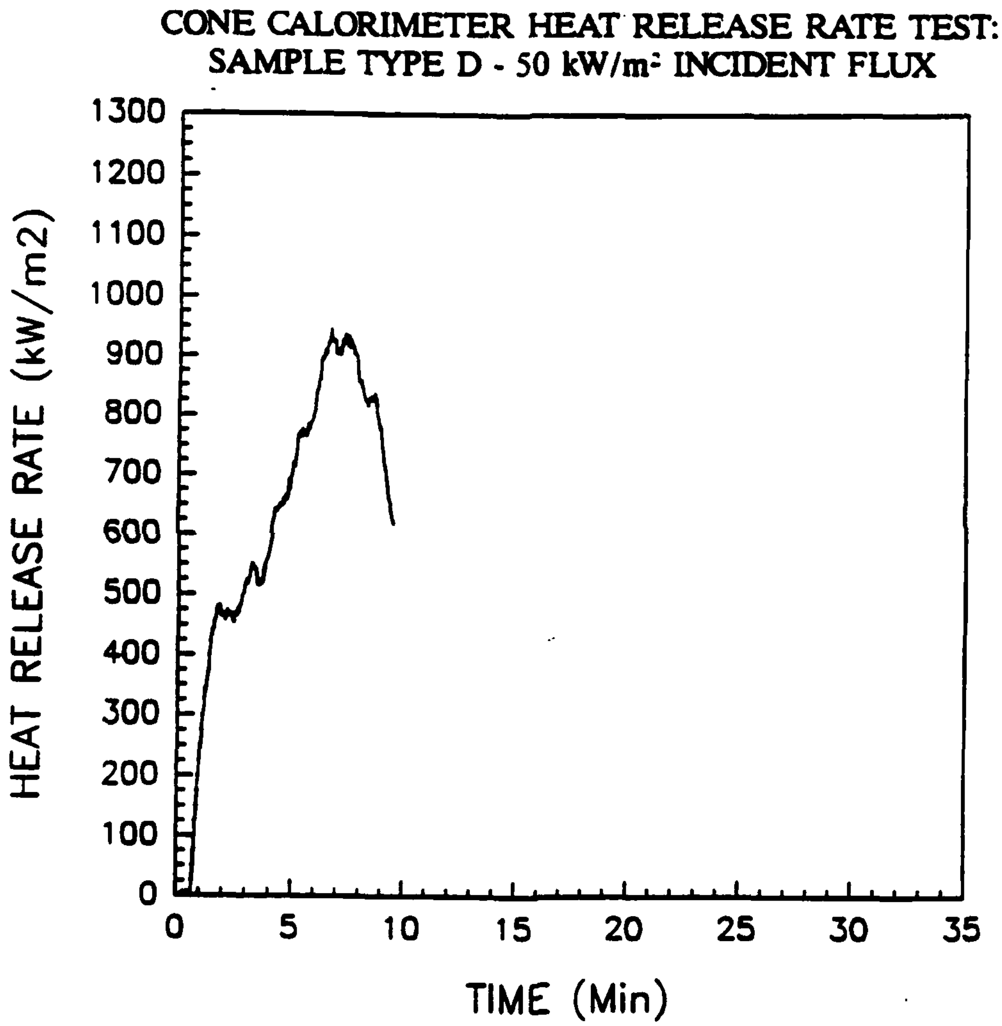
CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE D - 50 kW/m² INCIDENT FLUX
HEAT RELEASE RATE (kW/m2)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
TIME (Min)
0
5
10
15
20
25
30
35

Fig. A-11

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 75 kW/m² INCIDENT FLUX

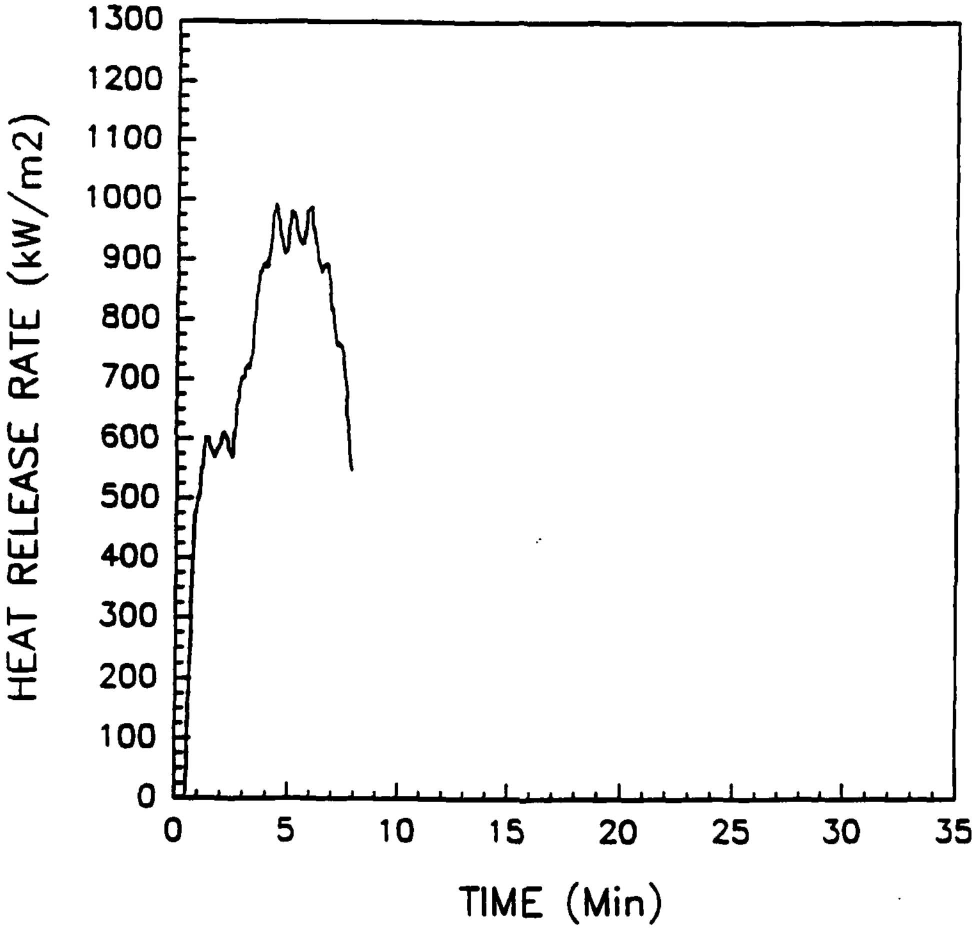

Fig. A-12

CONE CALORIMETER HEAT RELEASE RATE TEST:
SAMPLE TYPE A - 75 kW/m² INCIDENT FLUX

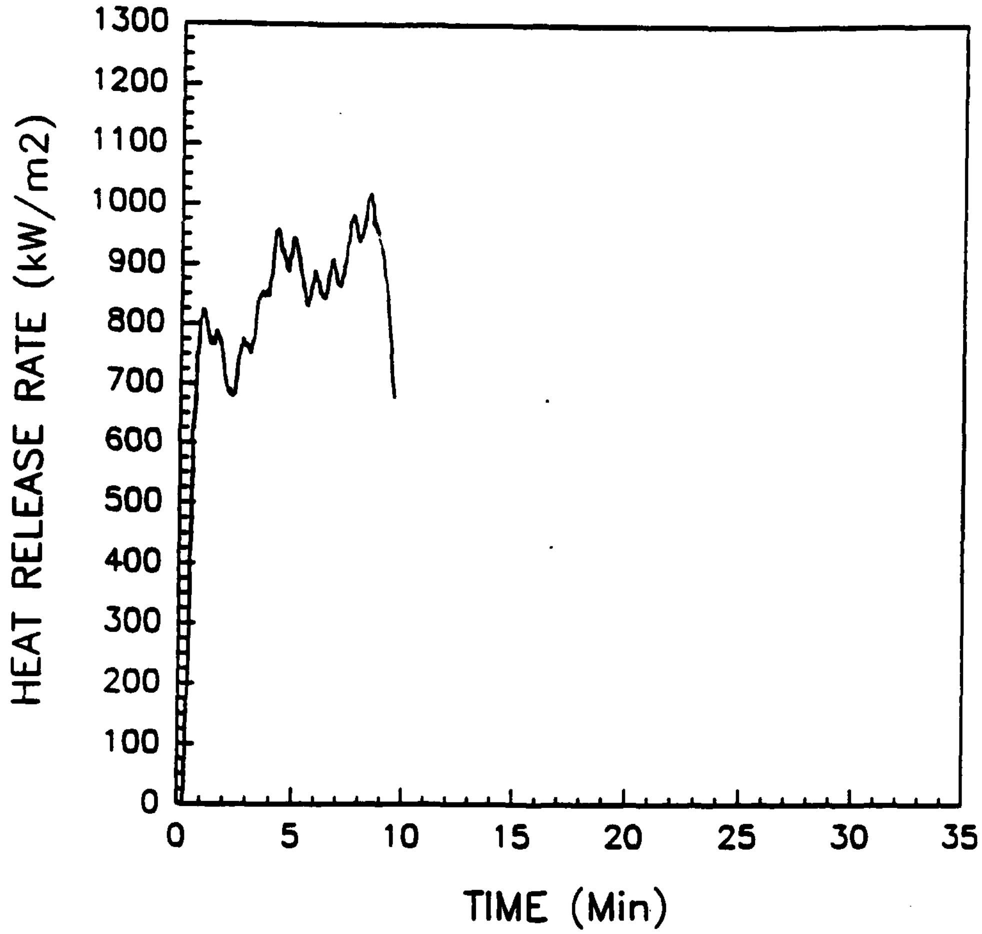

Fig. A-13

Appendix B

Selected Thermoplastics Material Properties

Table B1. Thermal Characteristics of Various Thermoplastics

Polymer	Bulk density [g/cm³]	Temperature resistance short term [°C]	Temperature resistance long term [°C]	Vicat-softening point B [°C]	Decomposition range [°C]	Flash-ignition temperature[3] [°C]	Self-ignition temperature[3] [°C]	Heat of combustion ΔH [kJ/kg]
Polyethylene LD[1]	0.91	100	80	–	340–440	340	350	46 500
HD	0.96	125	100	75				
Polypropylene	0.91	140	100	145	330–410	350–370	390–410	46 000
Polystyrene	1.05	90	80	88	300–400	345–360	490	42 000
ABS	1.06	95	80	110	–	390	480	36 000
SAN	1.08	95	85	100	–	370	455	–
PVC rigid	1.40	75	60	70–80	200–300	390	455	20 000
Polyvinylidene chloride	1.87	150	–	–	225–275	>530	>530	10 000
Polytetrafluoroethylene	2.20	300	260	–	510–540	560	580	4 500
Polymethyl methacrylate	1.18	95	70	85–110	170–300	300	450	26 000
Polyamide 6	1.13	150	80–120	200	300–350	420	450	32 000
Polyethylene terephthalate	1.34	150	130	80	285–305	440	480	21 500
Polycarbonate	1.20	140	100	150–155	350–400	520	[2])	31 000
Polyoxymethylene	1.42	140	80–100	170	220	350–400	ca. 400	17 000

[1] LD = Low density
HD = High density
[2] no ignition
[3] by ASTM D 1929

from Troitzsch, *International Plastics Flammability Handbook (Principles, Regulations, Testing, and Approval)*, 2nd edition, Hanser Publishers, NY, 1990, p. 22.

Appendix C

FMRC Small Array Plastic Storage Tests

Table C1. Summary of Small Array Plastics Storage Tests (Palletized Storage 2 x 2 x 3 high)

Commodity Description	Volume Fraction of Fuel (ϕ) (%)	Weight Percentage of Plastic and Cardboard	Approximate (± 20%) Weight Loss History (1) t: in min	Maximum HRR* (Btu/min)	Time of 1st Sprinkler Operation (min)	HRR *(2) at 1st Sprinkler Operation (Btu/min)	Sprinkler Rings** Opened	No. of Sprinklers
A. Commodities in compartmented cartons								
Test 4, jars, polystyrene 16 oz in compartment cartons	15	75% plastic 25% cardboard	$\Delta m = 15\ t^2$	$7.06 \cdot 10^6$	1.82	$8.75 \cdot 10^5$	1 + 3	13
Test 6 bottles PVC, 32 oz in compartmented cartons	16.4	50.3% plastic 49.7% cardboard	$\Delta m = 14\ t^3$	$2.38 \cdot 10^6$	1.68	$6.07 \cdot 10^5$	1	4
Test 15, bottles 16 oz polyethylene, in compartmented cartons	20	57% plastic 43% cardboard	$\Delta m = 8\ t^2$	$2.58 \cdot 10^6$	1.68	$4.03 \cdot 10^5$	1 + 3	13
Test 19, tubes, polypropylene, 16 oz in compartmented cartons	15	53% plastic 47% cardboard	$\Delta m = 8.5\ t^3$	$3.26 \cdot 10^6$	2.25	$5.51 \cdot 10^5$	1 + 3	12
Test 41, cardboard boxes compartmented without any plastic commodity	13	100% cardboard	$\Delta m = 17.5\ t^3$	$1.41 \cdot 10^6$	1.6	$4.48 \cdot 10^5$	1	4
B. Commodities loosely packed (including meat trays)								
Test 30A, toy parts, polystyrene	14	91% plastic	$\Delta m = 7\ t^3$	$2.19 \cdot 10^6$	3.43	$7.94 \cdot 10^5$	1	4
Test 13, meat trays wrapped in plastic sheet	2.7	100% plastic	$\Delta m = 19.5\ t^3$	$4.36 \cdot 10^6$	0.93	$1.10 \cdot 10^6$	1 + 3	13
Test 23, meat trays wrapped in paper	3.1	100% plastic	$\Delta m = 24\ t^3$	$4.5 \cdot 10^6$	0.95	$9.13 \cdot 10^5$	1 + 3	12
Test 44, tubes 16, 24, 32 oz polystyrene	–	92% plastic 8% cardboard	$\Delta m = 9.2\ t^2$	$2.78 \cdot 10^6$	–	–	–	–
Test 5, bottles, 16 oz Polyethylene	9.2	81% plastic 19% cardboard	$\Delta m = 1.1\ t^{3.8}$	–	5.90	–	1	4
Test 7, bottles assorted 1/2 12 oz, polyethylene	–	–	$\Delta m \cong 5\ t^2$	$1.44 \cdot 10^6$	5.28	$4.81 \cdot 10^5$	1	3
Test 22, trash barrels polyethylene	5.8	87% plastic 13% cardboard	$\Delta m = 4.35\ t^3$	$2.72 \cdot 10^6$	1.9	$7.72 \cdot 10^5$	1	3
Test 43, bottles 64 oz polyethylene	6		$\Delta m = 3.97\ t^3$	$2.46 \cdot 10^6$	–		1	4
C. Insulation boards								
Test 34, polyurethane foam *with paper facing*	–	71% plastic	$\Delta m = \begin{cases} 64t^4 & (t<1.5\text{min}) \\ 65t & (t>1.5\text{min}) \end{cases}$	$1.09 \cdot 10^6$	0.56	$5.04 \cdot 10^5$	1	4
Test 35, polystyrene board, no wrapping	–	100% plastic	$\Delta m \cong 4.41 \cdot 10^{-8.13}$					

* HRR: Heat Release Rate (estimated)
** 1: means first ring of sprinklers
3: means third ring of sprinklers

(1) See eqs (1), (2), and (3)
(2) See eqs (13) and (14)

from Delichatsios, *Fire Science and Technology*, 3 (2), 1983, p. 81.